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PROJECT REPORT

SELECTIVE SEPARATION OF COAL-PYRITE FROM COAL (DSS15SQ.23440-4-9189)

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1.0 SUMMARY

Results of a joint UBC-B.C. Research project on selective depression of coal-pyrite in coal flotation are presented.

A raw coal sample obtained from the Prince Mine (Cape Breton Development Corporation) in Nova Scotia was used in all testwork. Raw coal was stage crushed and washed initially on a shaking table to separate coarse mineral matter high in pyrite. Table reject (10-20% pyrite) was ground and used as substrate for growth of Thiobacillus ferrooxidans in batch and continuous culture.

Under steady state conditions, continuous bioleaching of pyritic table reject resulted in essentially complete oxidation of pyritic sulphur and produced solutions with large populations of active T. ferrooxidans bacteria. Retention time in the steady state leaching period was 110 h at an initial pulp density of 10% (w/v) and an initial pyrite concentration of 2% (w/v).

The bacterial suspension obtained by decantation of steady state leached slurry contained iron (III) (10-11.5 g/L) and its pH was in the range of 1.0-1.1. Content of bacteria by optical microscopy was in the range of 10^8 MPN/mL.

Run-of-mine coal for flotation testing was wet ground to 92% -400 mesh. Flotation tests with bacteria involved conditioning of 250 g coal with 1 L of bacterial suspension for a range of times and conditions, followed by pH adjustment (with or without solution exchange) and flotation under previously developed standard conditions.

Results of these tests indicated increased pyrite recovery to flotation concentrate and faster flotation kinetics. Detailed assessment of these and previous results led to the conclusion that pyrite from Prince mine coal is not hydrophobic. There is a good correlation between pyrite rejection and ash (non-sulphide) mineral matter rejection. The increase in pyrite flotation after conditioning with bacteria was, therefore, attributable to inceased entrainment at the observed higher flotation rate.

Further flotation tests on a 91% pyrite concentrate from ROM coal confirmed that this pyrite does not float with MIBC frother/kerosene collector. The pyrite can be floated with xanthate/kerosene/MIBC, and this flotation is enhanced by conditioning in dilute sulphuric acid.

Conditioning of pyrite with bacterial suspension prior to flotation with xanthate/kerosene/MIBC resulted in substantial (~50%) pyrite depression. However, conditioning with ferric sulphate (10 g/L) and dilute sulphuric acid provided equivalent or better pyrite depression. This suggests that the iron (III) content of bacterial suspensions (10-11 g/L) may be the effective depressant.

For the Prince Mine coal-pyrite (non-floatable with MIBC/kerosene), minimum levels of $\leq$0.5% pyritic sulphur in flotation concentrate were obtained by fine grinding and careful control of entrainment in flotation.

For conditions under which coal pyrite is floatable (in the current work by use of xanthate/kerosene), conditioning with bacterial suspensions provided significant depression but equivalent chemical (acid-ferric sulphate) treatment was also effective. Thus, while bacterial acidic ferric sulphate solutions may be cost effective for depression of floatable pyrite, the effect (if any) of the bacteria and/or bacterially produced surfactants can be obtained by chemical treatment alone under the same conditions with respect to ferric sulphate concentrations and pH.

With respect to depression of pyrite in other coal cleaning processes such as oil agglomeration, the observed (flotation) depression of pyrite by relatively short contact with concentrated biological leach solutions indicates that process economics may be improved by leaching of a highly pyritic reject.

Regardless of whether the depression in agglomeration systems is chemical, biological or mixed, continuous bioleaching of high pyrite rejects would be a preferred approach to minimize costs associated with leach tank volume and agitation requirements.

1.0 SOMMAIRE

Ci-dessous se trouvent les résultats du project de recherches sur la dépression sélective du charbon-pyrite dans une flottation de charbon. Les chercheurs de l'Université de la Colombie-Britannique et B.C. Research ont réunis leurs efforts pour réaliser ce travail.

L'échantillon de charbon brut obtenu de Prince Mine (Nova Scotia Development Corporation) en Nouvelle-Ecosse a été concassé par étape et lavé sur une table branlante pour séparer les mineraux bruts au niveau de pyrite élevé. La fraction rejetée par la table (10-20% de pyrite) a été broyée et fut ulilisé comme substrat pour l'élevage de Thiobacillus ferrooxidans en culture en lots et continuelle.

Sous un état de procédé continu, la bio-lixiviation (bio-filtration) des rejects de la table pyridique a résulté en l'oxidation complète du soufre pyridique tout en produisant une grande population de bacteries T. ferrooxidans actives. Le temps de rétention en état de procedé continu de était 110 heures pour une densité de pulpe initiale de 10% filtration (poids/vol) et une concentration de pyrite initiale de 2% (poids/vol).

La suspension bactérielle obtenue de la décantation de la boue de filtration obtenue du procédé continu contenait du fer (III) (10-11.5 g/L) et le pH etait 1.0-1.1. Le contenu de bactérie mesuré par microscope optique était environ 10^8 MPN/mL.

L'échantillon de charbon pour les essais de flottation a été broyé avec de l'eau à 92% passant à la maille 400. Les essais de flottation avec bactérie entrainaient le conditionnement de 250 g de charbon avec 1 L de suspension bactérielle pour une gamme de temps et conditions, suivi par l'ajustement du pH (avec ou sans l'échange de solutions) et la flottation sous des normes antérieurement établies.

Le résultat de ces épreuves indique un niveau de pyrite recouvrable élevé par rapport au concentré de flottation et des kinétique de flottation accéléreés. Une évaluation détaillée de ces résultats ainsi que ceux antérieures nous mène à la conclusion que le pyrite de Prince mine est non hydrophobrique. Il existe une bonne correspondance entre le reject de pyrite et le reject de cenore (non-sulphide) de matière minérale.

Le niveau élevé de pyrite de flottation après conditionnement avec bactérie est donc attribuable à l'augmentation de l'entrainement au niveau de flottation élevé qui a été observé.

D'autre essais de flottation avec une concentration de pyrite a 91% de charbon ROM ont confirmé que ce dernier ne flotte pas avec le collecteur MIBC kérosène/mousseur. La flottation du pyrite peut se faire avec le xanthate/kérosène/MIBC et ce deriner peut-être enrichi avec le conditionnement a l'acide sulfurique dilué.

Le conditionnement du pyrite avec une suspension bactérielle avant la flottation, et avec le xanthate/kérosène/MIBC, a donné une dépression de pyrite substentielle (~50%). Par contre, le conditionnement au sulfate ferrique (10 g/L) et à l'acide sulfurique dilué nous a fournis des résultats de dépression du pyrite equivalent ou supérieur a ceux antérieurement obtenue. Ceci suggère que le coutenu de fer (III) des suspension bactérielle (10-11 g/L) peut être le dépressant effectif.

En ce qu concerne le charbon-pyrite de Prince Mine (non flottable avec MIBC/kérosène), des niveau minimum de souffre pyriteque $\leq$0.5% en concentré de flottation, ont été obtenue par la monture fine et par le controle soigneux de l'entrainement en flottation.

Pour les conditions où le charbon pyrite est flottable (avec xanthate/kérosène), le conditionnement avec suspension bactérielle a fournis une dépression significative, cependant le traitement

chimique équivalent (sulfate de fer acidique) était aussi efficace. Ainsi, tandis que les soluions bactérielles de sulfate de fer acidique sont efficace a prix abordable pour la dépression de pyrite flottable, l'effet (si il en a) de bactérie et/ou de surfactant produit bactériellement, peuvent etre obtenue par seule, un traitment chimique sous le mêmes conditions à l'égard des concentrations de sulphate ferrique et du pH.

En ce qui concerne la dépression de pyrite, dans u'autre procedé de nettoyage du charbon, t'el que l'agglomeration des huiles, l'observation de la depression de pyrite par contact avec les solutions biologiquement lixivé, indique que l'économie du procedé peut-être augmenté par la lixivation des reject pyritique élevé.

Peut importe le type de dépression en system d'agglomeration (chimique, biologique ou melangé), la bio-lixivation continuelle de reject pyritique élevé est l'approche préférable pour réduire les côuts associé au volume de reservoir de lixivation et a l'agitation requis.

2.0 INTRODUCTION

2.1 Background

Removal of pyritic sulphur is a critical aspect of coal cleaning, particularly for (relatively) high sulphur coals from Eastern Canada. A portion of pyritic sulphur in these coals can be removed by conventional washing at coarse particle sizes, but rejection of fine granular or framboidal pyrite may present difficulties in cleaning of fine coal by froth flotation.

The University of British Columbia Department of Mining and Mineral Process Engineering (UBC-MMPE) has conducted studies on flotation of Eastern Canadian (Prince Mine) coal involving development of optimum procedures and evaluation of ash/pyrite depressants. Research elsewhere has indicated that the bacterium Thiobacillus ferrooxidans and/or its products can render pyrite hydrophilic and thus act as depressant(s) in coal cleaning by oil agglomeration (1) or froth flotation (2, 3).

B.C. Research has conducted applied research on biological leaching using T. ferrooxidans for over 20 years (4, 5). Investigations have included a wide variety of mineral substrates (chalcopyrite, sphalerite, pentlandite, mixed sulphide and ores). Recent work has concentrated on leaching of auriferous pyrite and pyrite-arsenopyrite ores and concentrates to enhance precius metals recovery. Facilities are maintained for batch and continuous leaching testwork.

In response to a CANMET/DSS Request for Proposal, B.C. Research and UBC-MMPE submitted a proposal for a joint study on use of pyrite bioleaching products for enhanced separation of coal pyrite from coal using flotation. This report presents results of the study conducted under DSS Contract 15SQ.23440-4-9189.

2.2 Objectives

The overall objective of the project was to investigate use of T. ferrooxidans bacterial suspension for selective depression for coal pyrite. Specific sub-objectives included continuous growth of T. ferrooxidans on coal pyrite, monitoring of bacterial populations in (mineral free) suspension and flotation tests with the bioleach product solutions.

3.0 MATERIALS AND METHODS

3.1 Coal Samples and Preparation

A 0.75 tonne sample of current (as of June, 1985) run of mine (ROM) coal was obtained from the Cape Breton Development Company (Devco) operators of the Prince Mine in Nova Scotia.

The ROM coal was crushed to ~1 cm topsize, blended by coning and quartering, and stored in steel drums for subsequent further processing by tabling for coarse pyrite concentration or grinding/ flotation.

A sample of ~50 kg of hand picked high pyrite coal was also provided by Devco. This material was crushed, rod milled and passed over a Wilfley table to concentrate pyrite for bioleaching.

Pyritic concentrates were ground to 75% -325 mesh prior to use in leaching tests.

3.2 Biological Leaching Tests

3.2.1 Culture Preparation

A culture of *T. ferrooxidans* previously maintained on pyrite was used to inoculate pulps of 10% solids (~1% pyrite in pulp) prepared from Prince Mine table reject. Initially, pH adjustment to 2.2 with H_2SO_4 was required, but in subsequent serial transfers, a 10% inoculum provided adequate pH adjustment due to high ferric sulphate content of leach solution. Standard iron free 9K nutrient salts ($(NH_4)_2SO_4$, 3 g/L; K_2HPO_4, 0.5 g/L; $MgSO_4 \cdot 7H_2O$, 0.5 g/L; KCl, 0.1 g/L; $Ca(NO_3)_2$, 0.01 g/L were used to make up all leach solutions.

All leaching tests were performed in a controlled environment room (35°C, CO_2 enriched air).

3.2.2 Batch Leaching

After culture preparation, batch leaching at 10% pulp density in 2 L agitated tanks was initiated. Initially, acceptable leaching rates were obtained. However, it was found impractical to synchronize these tests with flotation testwork and delayed transfer of inoculum resulted in poor leaching.

3.2.3 Continuous Biological Leaching

A continuous bioleaching reactor system as shown in Figure 1 was set up to provide conditions for high oxidation of coal-pyrite and a reasonably stable supply of bacterial suspensions for flotation testing. The 5 L feed tank allowed continuous operation over weekends; the following 2 reactors in series provided residence time for substantial pyrite oxidation. The fourth tank in series provided holding capacity for leached slurry under favourable conditions for bacterial survival so that well mixed samples of reasonably constant composition could be withdrawn as required for flotation testwork.

The configuration of individual leaching tanks (Figure 1) has been shown to provide optimal conditions for growth of T. ferrooxidans. Mixing and turbulence are maintained by baffles and turbine mixing (0.035 HP/L); air enriched with 1% CO_2 is sparged under the turbines at a controlled rate to ensure constant air saturation. Slurry transfer through the system was maintained with calibrated peristaltic pumps operated on a timed cycle to maintain required slurry flows.

Bacterial suspensions for analysis and/or testing were obtained by withdrawing slurry from the fourth tank, quiescent settling for 3-4 h and decantation of (essentially) mineral free supernatant.

3.3 ANALYTICAL PROCEDURES

3.3.1 Chemical Analyses

Leach solution iron values were determined by atomic absorption using a Perkin Elmer model 306 spectrophotometer. Iron analyses on pulps were performed by atomic absorption following digestion in bromine and aqua regia.

Total sulphur was determined by digestion of the sample in bromine and aqua regia, followed by sulphur precipitation as barium sulphate.

Slurry pH values were measured using a calibrated Fisher Accumet pH Meter, Model 610 A.

Total Kjeldahl Nitrogen (TKN) was determined on mineral free solution by millipore (0.45 microns) filtration; the pad was then washed with dilute (pH 1.) HCl to eliminate any unsettled ammonia jarosite or other inorganic reduced nitrogen and digested/distilled for determination of total biomass nitrogen by standard methods.

Total organic carbon measurements were done by direct injection of mineral free supernatant to a Beckman "Tocamaster" TOC Analyzer, Model 615B.

3.3.2 Optical Microscopy

Bacterial suspensions were examined using a Wild biological microscope (600 x, oil immersion) using pendant drops of suspension on a cover slip. Motile (ie. actively moving) bacteria were estimated and serial dilutions were performed until an average of 5-10 bacteria were visible in each field. Counts (most probably number or MPN) were calculated from field volume and dilution of the initial sample.

A Brinkman particle size analyzer (Model 2010X) with an "image visualization" subsystem was used to obtain video and computer generated print images of clean and actively leaching pyrite samples.

3.4 Flotation Test Procedures

Methods, results and discussion of the flotation testing component of the project are presented in the UBC-MMPE report presented as Appendix 1.

4.0 RESULTS AND DISCUSSION

4.1 Bacterial Leaching of Prince Mine Coal-Pyrite

4.1.1 Adaptation and Batch Tests

Adaptation of T ferrooxidans to the Prince Mine pyrite (table reject, ~10% FeS_2, 84% ash) presented no problems. Initial acid demand was 60 kg/tonne, but in succeeding shake flask transfer no further acid addition was required.

Results of larger scale (2 L tank) batch tests were initially satisfactory, but leach rate, pyrite conversion and bacterial population declined due to a combination of factors including delayed transfer and the long quiescent settling period (3-5 h) required to produce an acceptable - ie. >2/L - volume of mineral free supernatant for flotation tests.

4.1.2 Continuous Bioleaching Tests

Iron and sulphur contents of the feed materials for the continuous bioleach system are presented in Table 1. Performance data for the continuous bioleach system are presented in Figure 2, 3 and 4.

As shown in Figure 2, average retention time in the leaching system including the holding tank (Reactor 3) was initially held at 10 days. Subsequently, retention time was reduced by increasing slurry flow to increase the amount of product available for flotation testing. Abrupt variations in average residence time were due to accumulation in Reactor 3 of large volumes of slurry either over weekends or collected to provide large volumes of solution for flotation tests. Iron leaching rates during the initial period up to 38 days of operation were low (18-50 mg/L/h), reflecting the low pyrite content of feed.

For the second and third feed materials (22-26% FeS_2), higher and generally more consistent rates in the range of 60-80 mg/L/h were obtained. Total retention time was generally held at 7.5 days to provide iron extraction $\geq$70% (Figure 2), below which the concentration of motile bacteria in solution is generally lower.

For the final 80 days of bioleach operation, ie. after switching to a higher pyrite feed, system operation (Figure 2) was quite stable with respect to measured operating parameters including iron leach rate (65-80 mg/L/h), and iron extraction (80-100%).

As a qualitative observation, it was noted that pyrite in the feed tank did not form a visible surface layer or froth of unwetted material. Such a layer is characteristic of strongly hydrophobic materials such as chalcopyrite, even after extensive regrinding and oven drying.

Figure 3 shows pH levels in each of the reactor tanks. With the high pyrite feed, ie from day 38 onward, there was a trend to lower pH in the systems. Results indicate a stable final (ie. 100% pyrite oxidation) pH in the range of 1.1-1.0. From previous experience, this is the lower end of the pH range in which good biological oxidation rates can be obtained.

Figure 4 shows dissolved iron levels in each of the three reactors. These data indicate that after day 38, with high pyrite feed, most of the active leaching occurred in Reactor 1. The downtrend in dissolved iron for Reactors 2 and 3 up to day 38 indicates that substrate (pyrite) content of the feed was too low, which probably would have led to washout if this feed had been continued.

Consistent iron concentrations of 9-11 g/L in Reactors 2 and 3 are of interest with respect to flotation test data on xanthate activated pyrite (see below and Appendix 1, Table 5), or potential application of bioleach solution to oil agglomeration.

Data on optical bacteria counts and supernatant fixed nitrogen are presented in Figure 5. Bacterial counts in Reactor 1 were uniformly low as expected due to the continuing supply of fresh pyrite to this reactor. Qualitatively, supernatant bacteria concentration in Reactors 2 and 3 are also low relative to numbers observed in leach solutions from mineral concentrates. This may be due in part to the extended quiescent settling times (3-5 h) required to obtain adequate quantities of mineral free liquid for test purposes.

Attempts to estimate biomass chemically by total organic carbon (TOC) and total Kjeldahl nitrogen (TKN) were unsuccessful. High and erratic TOC levels indicated some organic dissolution from coal.

TKN values were too low to be used as a reliable index of biomass.

4.1.3 Imaging of Pyrite-Bacteria Under Active Leaching Conditions

At the request of the Scientific Authority (Dr. K. S. Moon), attempts were made to photograph pyrite - bacteria assemblages under slurry leaching conditions. Optical microscopic techniques were not successful, but video images (computer printed) presented as Figures 6 and 7 show a qualitative surface roughness difference in leaching vs clean pyrite particles. The bacteria are not fully opaque to visible light, so interference patterns from the bacteria - as well as surface roughness induced by leaching - are potential contributors to the qualitative difference in appearance.

4.2 Flotation Program

Results and discussion of the UBC-MMPE are presented as Appendix 1.

A major conclusion of this work is that the pyrite content of tested Prince Mine Coal is not hydrophobic in the presence of reagents (MIBC/Kerosene) required for coal flotation. Thus the uniformly higher pyritic sulphur content of coal floated after bacterial conditioning is attributed to higher flotation rates and consequent higher entrainment of fine mineral matter including pyrite.

To investigate biodepression of floatable pyrite, it was necessary to use a xanthate/kerosene/MIBC reagent combination.

With this combination, Prince Mine pyrite was 78.5% floatable even at coarse size in Hallimond Tube tests. Preconditioning of the pyrite with sulphuric acid before xanthate flotation further increased recovery to 85.4%

Conditioning of pyrite with bioleach solution (containing ~ 10g/L iron [111]) reduced pyrite recovery to 42.6%, but essentially the same pretreatment without bacteria (ie. 10 g/L Fe [111] as sulphate, pH 1.5) resulted in even more effective pyrite depression (16-18% recovery, or roughly the amount of mechanical carryover).

This clearly indicates that the iron content of bacterial leach solutions is an important factor - or perhaps the predominant factor - in depression of pyrite for subsequent flotation.

4.3 Applicability of Results to Practical Coal Cleaning Systems

Applicability of the current results to a (hypothetical) naturally hydrophobic, floatable, coal-associated pyrite is questionable. However, for oil agglomeration cleaning conditions under which pyrite is recovered with coal, the current data certainly suggest that the iron (111) sulphate content of bioleach solution is an important factor for pyrite rejection in subsequent agglomeration. If this is the case, then bioleaching of coal-pyrite is liable to be a cost-effective source of ferric sulphate. Conditioning of fine coal with (as indicated by current test data) 10 g/L Fe (111) solution will lead to significant ferric sulphate consumption from the aqueous phase, regardless of how the coal is separated from the conditioning solution.

Power cost for oxygen transfer is the predominant operating cost in bioleaching, and can be conservatively estimated at 0.5 Kwh (e)/kg oxygen dissolved from air. Thus, power requirement per tonne of pyrite oxidized is roughly 570 kwh or, at $0.05/kwh, $28.30 per tonne of pyrite oxidized or $10.20 per tonne tonne of $Fe_2(SO_2)_3$. This compares very favourably with commercial iron sulphate costs of $100-150 tonne (6).

The potential for application of this approach - ie. bioleaching pyrite to produce ferric sulphate for depression of pyrite in agglomeration - would require determination of ferric sulphate consumption and conditioning pH for pyrite rejection from specific coal(s). If ferric sulphate is effective at low addition levels and normal coal slurry pH values, the capital cost of a bioleach reactor would not be justified. If high additive levels and/or low pH conditioning were required, minesite generation of acidic ferric sulphate by bioleaching of pyrite could be cost-effective. An inherent assumption is that in this approach is that the required amount of pyrite could be recovered at low cost and $\geq$20% concentrations (dry basis) from coal rejects.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Bioleaching of Prince Mine Coal Pyrite

Continuous bioleaching of Prince Mine coal-pyrite has been demonstrated. For rejects containing pyrite at 20-25 wt %, pyrite conversions of 80-100% are readily obtainable. At 10% pulp density, product solution pH is in the range of 1.0-1.3 and iron (III) content in the range of 9-12 g/L. Higher leaching rates and dissolved iron levels could readily be obtained with higher pulp density or (preferably) higher pyrite content of bioleach feed.

5.2 Selective Biodepression of Coal Pyrite in Flotation

Detailed conclusions are presented in Appendix 1. In summary:

- Prince Mine coal-pyrite is not hydrophobic.
- Conditioning of Prince Mine coal in bioleach solutions results in increased pyrite recovery to coal concentrate due to entrainment.
- Ferric sulphate content of bioleach solution is probably the major factor leading to partial depression of pyrite in xanthate activated flotation after preconditioning in bioleach solution.

5.3 Depression of Pyrite in Oil Agglomeration

Current results indicate that ferric sulphate is effective in depression of pyrite towards floatation by Xanthate/kerosene. By inference, ferric sulphate could be the active agent in previously observed depression of pyrite in oil agglomeration of coal.

If high addition levels of ferric sulphate and/or acidic conditioning are required, bioleaching of coal pyrite is a potentially cost-effective approach to minesite production of the required materials.

Justification of further work in this area would require determination of ferric sulphate and acid reagent requirements for effective depression of pyrite in oil agglomeration.

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6.0 REFERENCES

1. Kempton, A.C., C.E. Capes and R.G.L. McCready, "Removal of pyrite from coal by conditioning with Thiobacillus Ferrooxidans followed by oil agglomeration", Hydrometallurgy, 5, 117, (1980).

2. Attia, Y.A. and M.A. Elzeky, "Biosurface modification in the separation of pyrite from coal by froth flotation", Proceedings of the First International Conference on Processing and Utilization of High Sulfur Coals, Elsevier, (1985), pp. 673-682.

3. Dogan, M.Z. et al. "Bacterial leaching versus bacterial conditioning and flotation in desulphurization of coal", XVth International Mineral Processing Congress, 2, 304 (1985).

4. Razzell, W.E., Bacterial Leaching of Metallic Sulphides, CIM Bulletin, March, 1962.

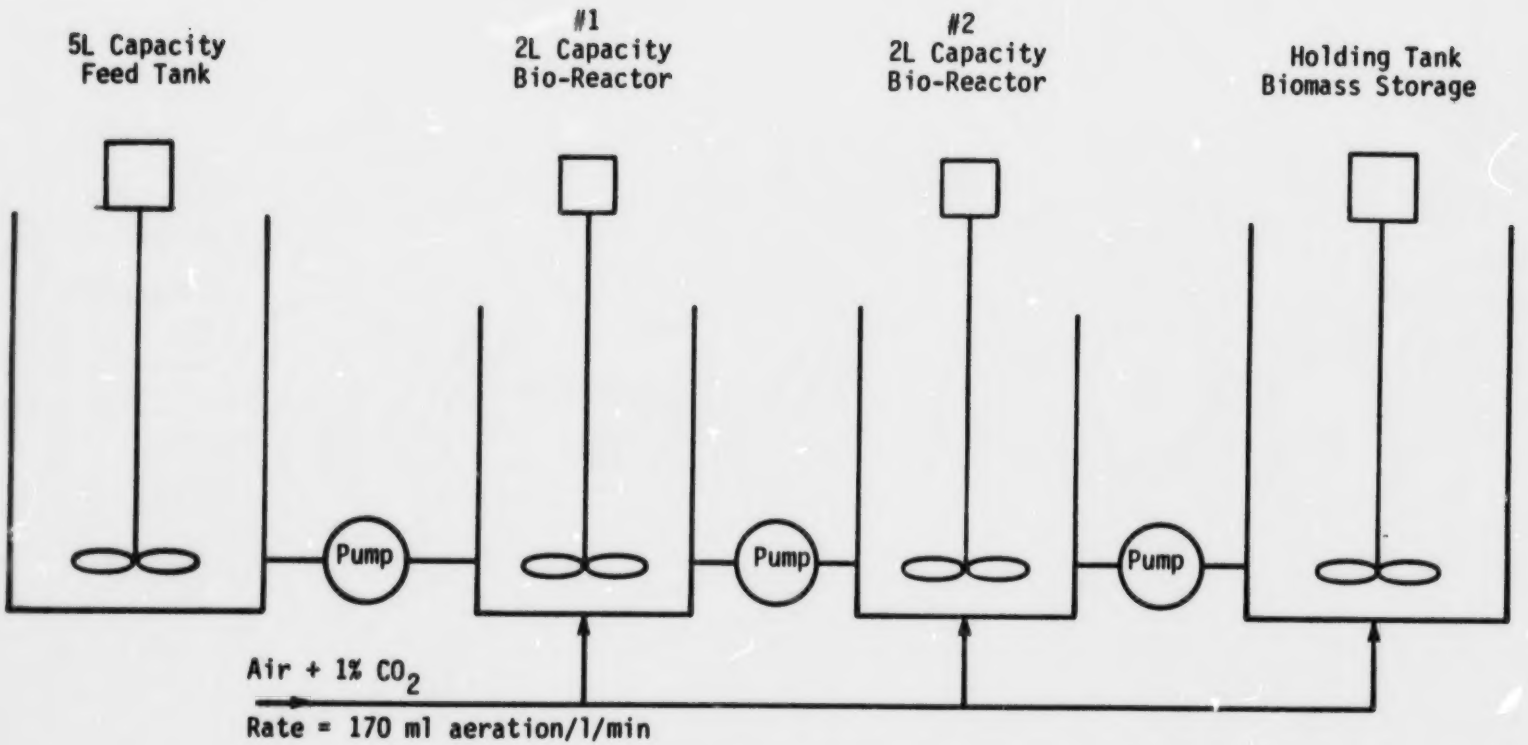
5. Lawrence, R.W., A. Vizsolyi, R.J. Vos. In: Microbiological effects on metallurgical processes. Edited by L.A. Haas and J.A. Clum. New York, AIME. 1985.

6. Anon, Chemical Marketing Reporter, 22, 19, May 12, 1986.

TABLE 1

Analyses of Feed Materials for
Continuous Bioleaching of Coal-Pyrite

Feed	Components (%, dry basis)			Period of Use (days)
	Fe	S_{tot}	ash	
1. BCR Table Reject from ROM Prince Mine Coal	6.0	5.5	84	0-37
2. Mixed BCR + UBC-MMPE Table Reject from Prince Mine Coal	11.0	13.0	96	38-82
3. Mixed BCR Table Rejects (reconcentrated) from Prince Mine Coal	10.3	11.5	93	83-135



Stirring motors: Cole Parmar 1/14 hp. stirrers
Pumps: Cole Parmar Peristaltic pumps

FIGURE 1: Continuous 3 Stage Bioleach System

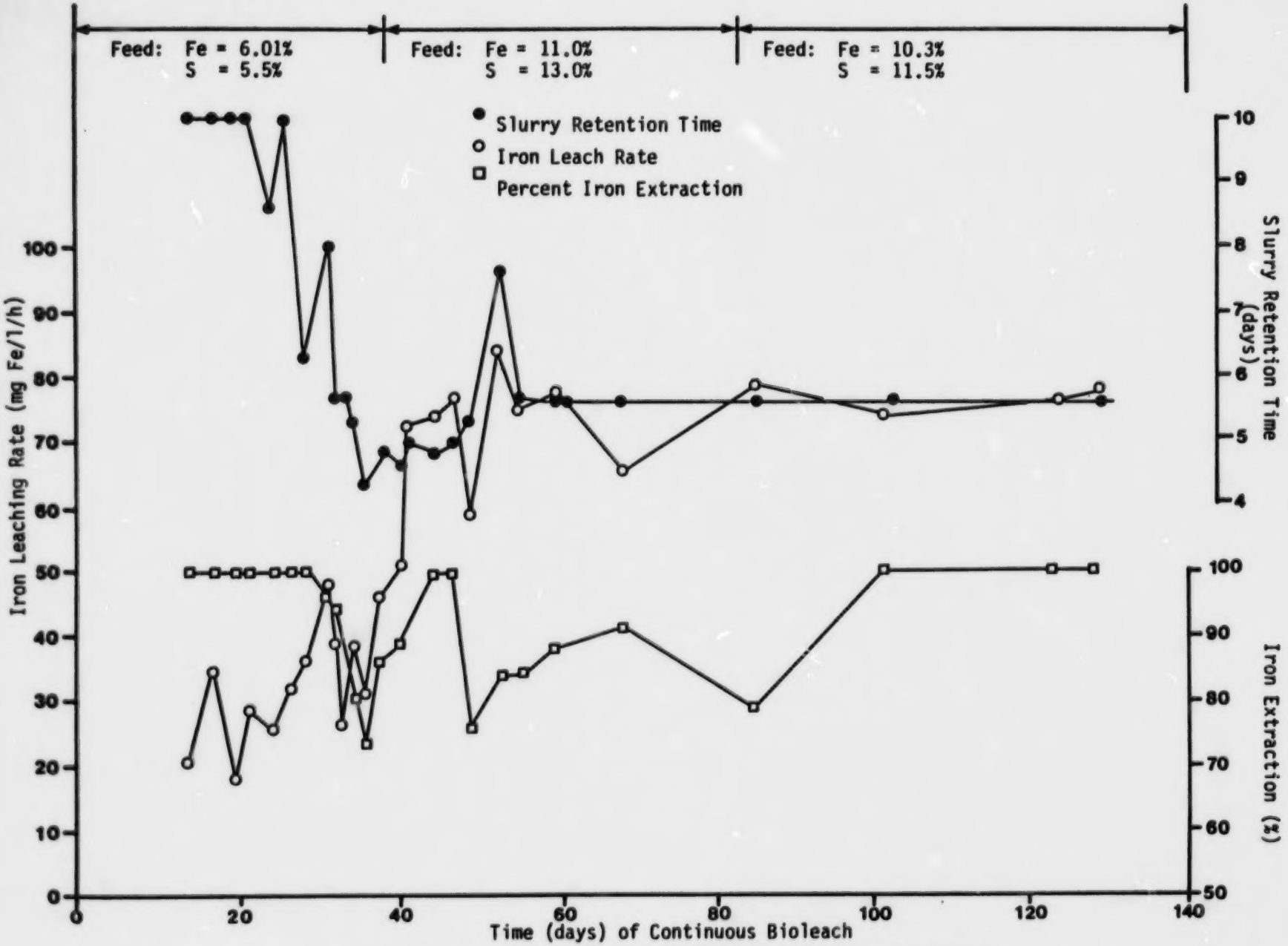


FIGURE 2: Iron Leach Rate, Extraction and Retention Time in 3 Stage Bioleaching of Coal Pyrite

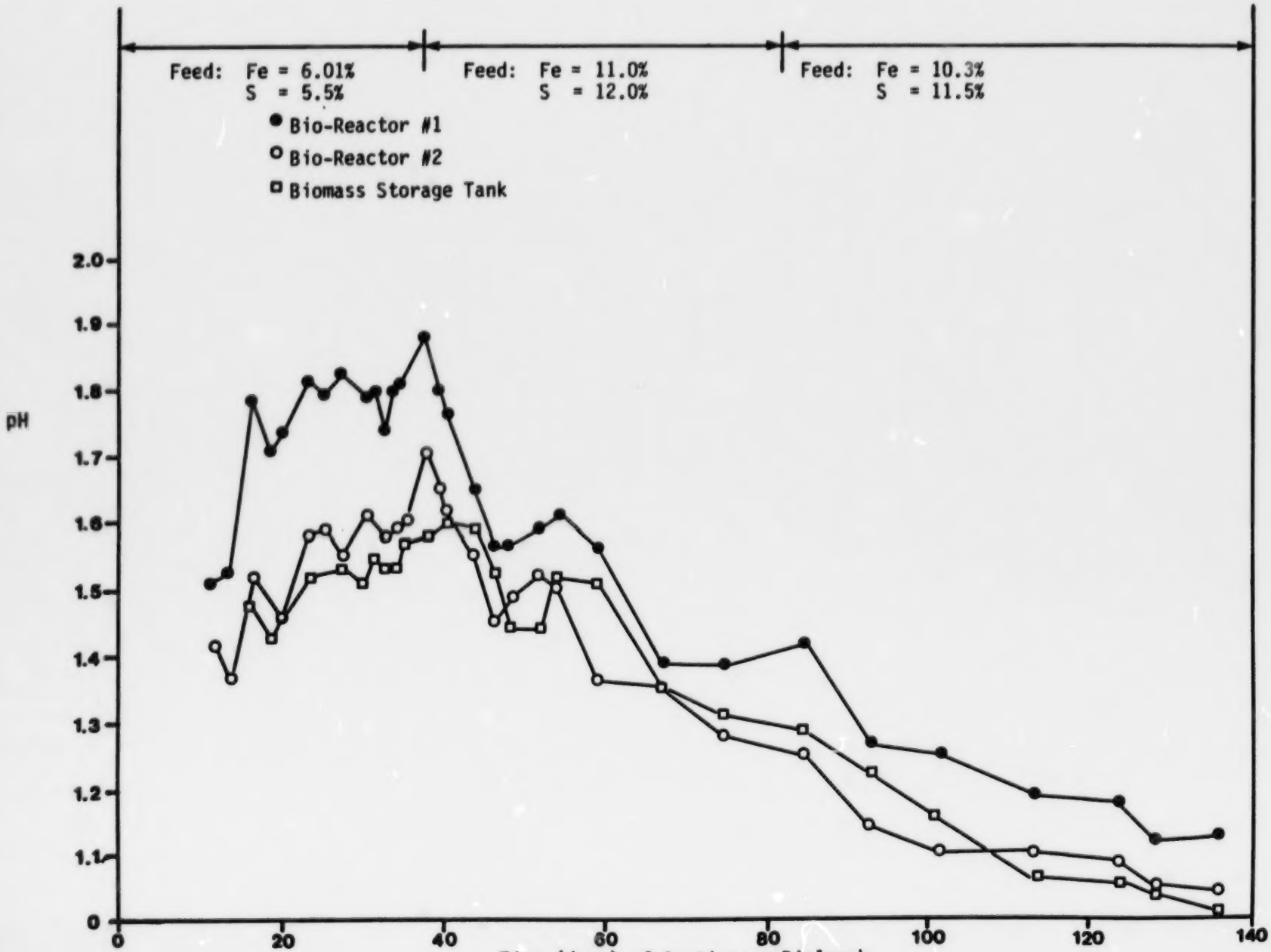


FIGURE 3: pH in 3 Stage Continuous Bioleaching of Coal Pyrite

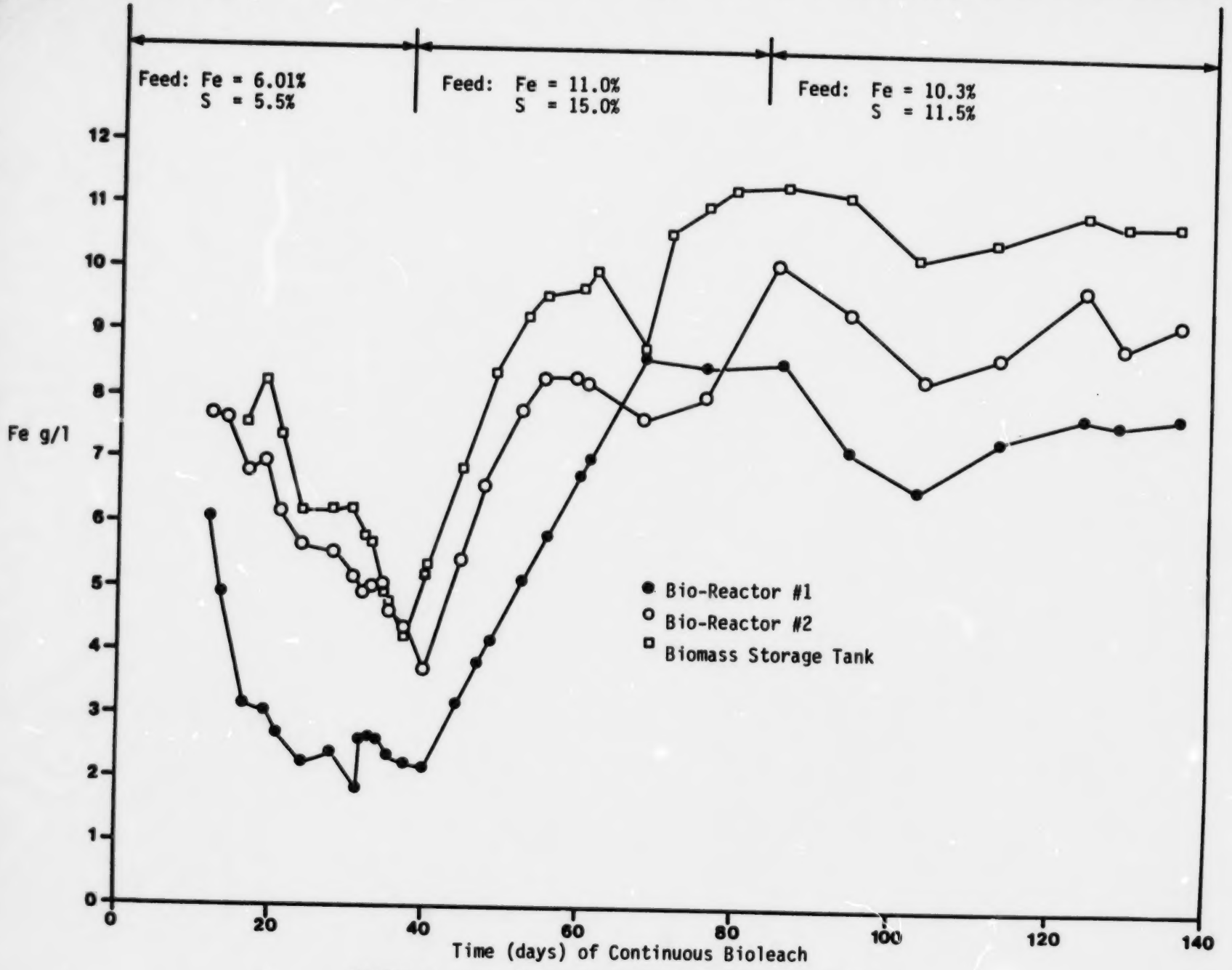


FIGURE 4: Iron Concentrations in 3 Stage Bioleaching

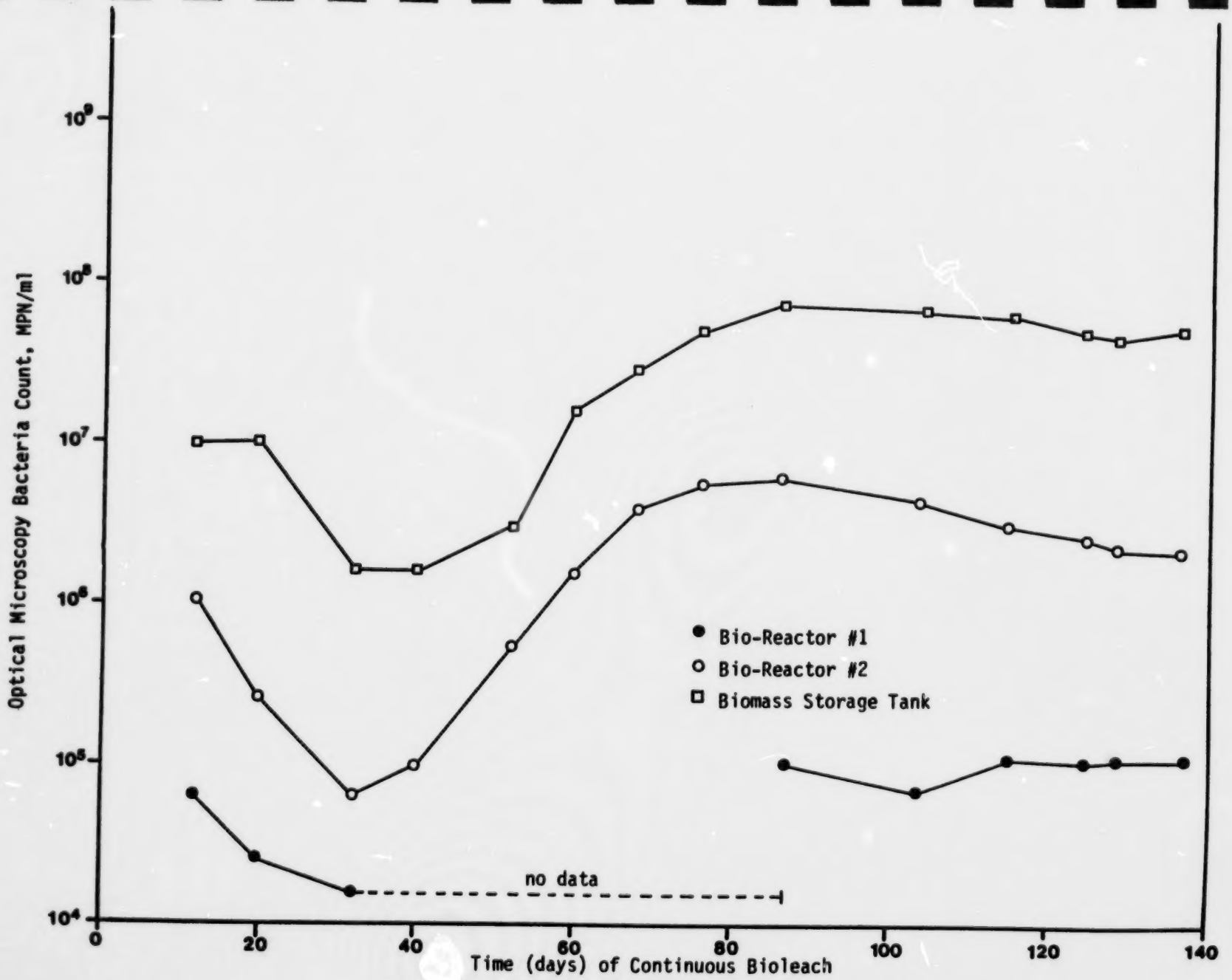


FIGURE 5: Bacterial Populations in Supernatant Solution Estimated by Optical Microscopy

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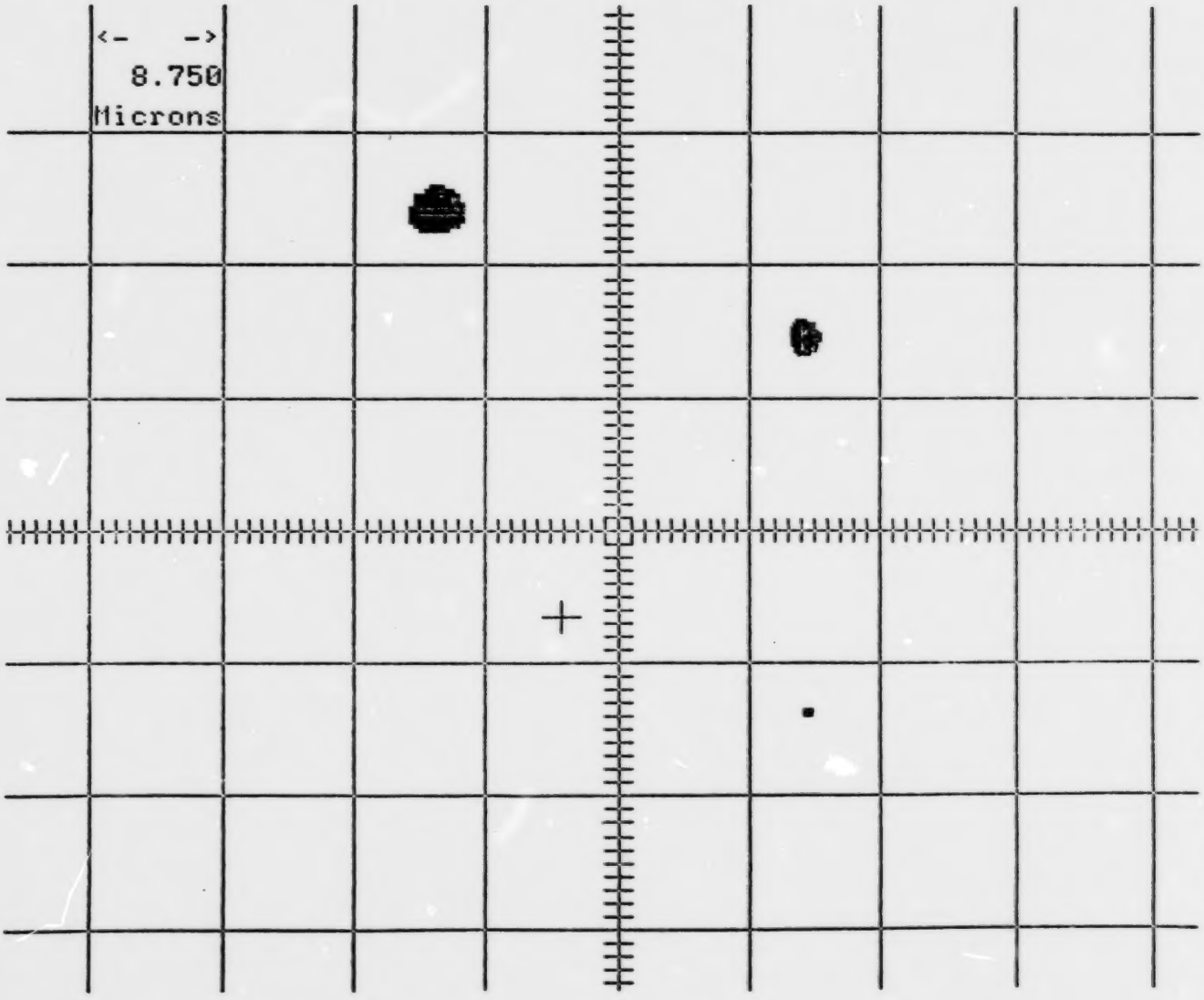

FIGURE 6: Videomicroscope Image of Pyrite Particle During Bioleaching

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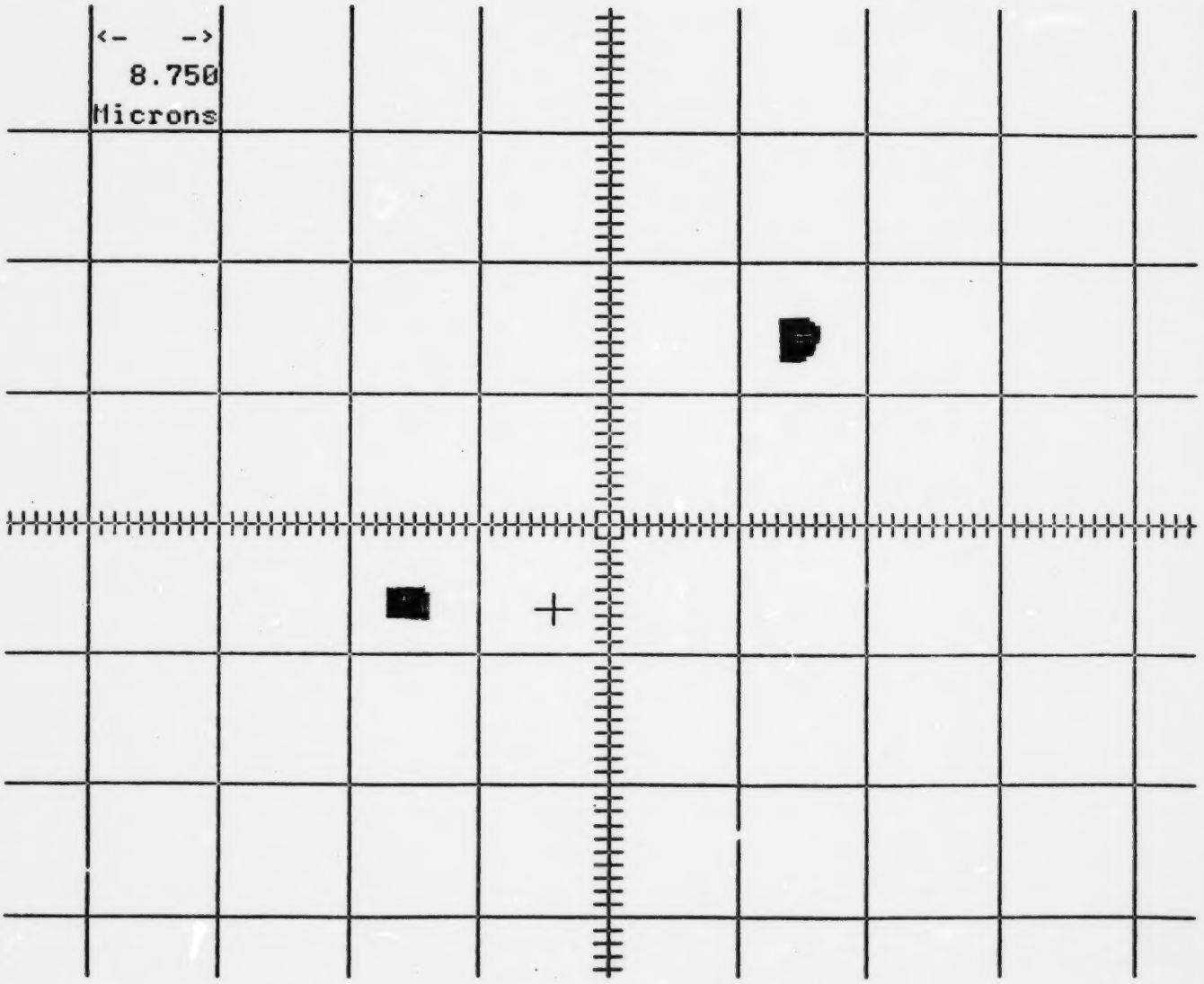

FIGURE 7: Videomicroscope Image of Clean Pyrite

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APPENDIX 1

Selective Separation of Coal-Pyrite from Coal by Flotation

Selective Separation of Coal-Pyrite from Coal by Flotation

Final Report

Department of Mining and Mineral Process Engineering
The University of British Columbia
Vancouver, B.C.

Project Manager: Dr. J. Laskowski

DSS File Number: 15SQ 23440-4-9189
CANMET Scientific Authority: Kwang S. Moon

INTRODUCTION

Desulphurization is one of the main reasons for cleaning coal. The large difference between the density of coal (1.2 - 1.6 g/cm^3) and that of pyrite (about 5.0 g/cm^3) provides the basis for efficient separation of pyrite from coal by gravitational methods. Although such methods are very efficient in separating coarse coal from coarse pyrite, their efficiency decreases drastically with decreasing size of particles. Because sufficient pyrite liberation often requires fine grinding, flotation becomes a major separation process. However, as shown by Trahar and discussed recently by Warren [1], while apparent floatability increases with decreasing size of particles, true floatability reaches an optimum around a few microns in diameter and decays with a further decrease in size. This indicates that the contribution from entrainment to overall flotation results increases for finer particles. Since the amount of particles carried over to the froth by entrainment is proportional to the amount of water in the froth, the process becomes less selective for finer feeds.

The coal flotation process is based on differences in surface properties between hydrophobic low-ash coal particles, and hydrophilic high-ash gangue. The coal-pyrite surface properties are not yet fully understood. It is generally believed that coal-pyrite particles are floatable with a flotation rate lower than that for coal [2], and therefore they differ significantly from ore-pyrite particles [3]. Recent studies also revealed that the two-stage reverse flotation

process was not effective for all coals. Miller and Lin [4] have shown that while well liberated granular pyrite particles are rejected during the first stage flotation, separation of the framboid particles, which are assemblies of pyrite crystals 1 μm in diameter, can be difficult.

It has also been reported that the pyrite in the finely ground coal is apparently rendered hydrophilic by a bacteria culture and is rejected when the coal particles are recovered either by flotation or oil agglomeration [5,6,7]. The biological and/or chemical mechanisms of this proposed process have not yet been fully elucidated [5]. However, many possibilities exist: selective adsorption of the bacteria cells onto the pyrite surface [8,9], wetting with surface-active substances produced by the thiobacillus bacteria [10,11,12,13,14], and the effect of inorganic substances present in the bacteria solution.

Investigations on the feasibility of using bacteria to depress pyrite in finely ground coal was undertaken with the assistance of B.C. Research. B.C. Research supplied active cultures of bacteria while the effect of the bacteria on desulphurizing flotation of the Prince Mine coal was studied at the University of British Columbia.

MATERIALS AND METHOD

Coal Sample

The Prince Mine coal sample characteristics are shown in Table 1. The sample is comparable to that which had been studied previously [15].

Coal Preparation

The procedure used in the flotation experiments was identical to that described previously (Figure 1). Grinding according to this procedure produced coal that was 92% below 38 μm (400 mesh), ensuring a high degree of pyrite liberation [15].

Bacterial Conditioning and Flotation

In bacterial conditioning tests, 250 g of 92% -400 mesh coal was placed in the flotation cell with the addition of 1 liter of an active culture of bacteria and stirred at 1200 rpm at the natural pH (1.7-2.2) of the bacteria coal slurry (at 20-25°C) for a specific period of time, with the air on or off. After conditioning, the slurry was either filtered and resuspended at the desired pH, or the pH was adjusted directly with NaOH. The coal was then floated as schematically illustrated in Figure 2 with the use of a Denver cell modified by Roberts et al [16]. The pulp level in the cell was

maintained by either the direct addition of bacteria culture or through the use of a constant level device which would admit pH regulated solution to the cell.

RESULTS

As can be seen from Figure 3, conditioning the coal with bacteria prior to flotation results in an increased level of pyrite in the clean coal concentrate. Although this figure shows only three tests, none of the tests through the course of the entire project, regardless of the conditions employed, showed encouraging results. The observed rates of flotation as illustrated in Figure 4 are higher for the coal that had been preconditioned with the bacteria. The higher level of pyrite in the coal floated in the presence of the bacteria can possibly be attributed to mechanical entrainment.

If the mechanical entrainment is as significant as Figures 3 and 6 imply, it follows that the modifications made by Roberts et al [16] would compound the problem. Tables 2 and 3 from Roberts et al [16] paper reveals that the modifications indeed cause an increase in the ash content in the concentrate. Although this increase in ash is modest for the conditions employed by Roberts et al, it should be noted that the average size for the Prince Mine coal in our tests is almost two orders of magnitude finer and so the conditions employed in the flotation of the Prince Mine coal would further aggravate entrainment. The effect of the modifications made by Roberts et

al [16] on the pyrite level in the clean coal concentrate is shown in Figure 5. It confirms the suspicion that entrainment is quite significant.

In the various tests performed with the bacteria and with kerosene and MIBC in the presence and absence of CMC, regardless of conditions employed, it was observed that the pyrite level in the clean coal concentrate was interrelated with that of the ash. This correlation is shown graphically in Figure 6. It suggests that the pyrite follows the ash; since the pyrite is believed to be mainly liberated and is not interlocked in the gangue material, the pyrite and the ash must have similar surface properties, namely that both are hydrophilic.

Additional tests with pyrite

Since the pyrite contained in the Prince Mine coal sample did not seem to float, we found it necessary to conduct additional tests on its surface properties.

Fig. 7 outlines the procedure that was used to separate pyrite from coal.

As seen from the results of Figure 8, the pyrite did not float with kerosene and MIBC, which seems to confirm its hydrophilic character. At the airflow employed, the mechanical entrainment for this cell was determined to be 31%; for the airflow rate reduced from 80 cc/min to 30 cc/min, the recovery dropped further from

over 30 % to about 15 %. The conclusion therefore was that the pyrite did not float under such conditions.

The results of the previous tests (tables 2 and 3 [17]), replotted in Fig. 9, show a correlation similar to that depicted in Figure 6. Although this correlation differs slightly from that in Figure 6, the difference is not significant and probably reflects an experimental error.

Because the pyrite separated from the Prince Mine coal which was utilized in these tests did not float in the presence of MIBC and kerosene, it was impossible to study the effect of the bacteria on its floatability. To enhance the floatability, xanthate together with kerosene were employed in the following Hallimond tube experiments.

In these tests (Table 4), 1 g of pyrite was conditioned for 25 min either with H_2SO_4 or bacteria solutions (pH 1.3-1.4), decanted several times with distilled water, and then conditioned at pH 4.7-5.3 with KAmX (0.2 kg/t) and kerosene (6 kg/t) for 1 min, and floated for 2 min at 30 cc/min airflow rate.

As seen from Table 4, the experiments in distilled water without reagents gave 12.5% recovery (mechanical carry over), KAmX without kerosene gave 25.5%, but KAmX together with kerosene provided 78.5% recovery. The pyrite recovery after conditioning with the bacteria prior to flotation dropped to 42.6%, but conditioning with H_2SO_4 (pH 1.5) led to quite satisfactory results, 85.4% recovery.

These tests then indicate that conditioning of the pyrite with bacteria solution prior to the flotation with KAmX and kerosene depresses pyrite floatability, while conditioning with H_2SO_4 solution at the same pH improves the final flotation results.

Since the bacteria solution as received from B.C. Research obviously contained a high quantity of iron, further tests were necessary to specify whether depression in the presence of bacteria was indeed caused by the bacteria or by ferric ions. The results of these tests are outlined in Table 5. The effect of the time of conditioning was examined, too. Two procedures, which employ either decantation as already described, or centrifugation, were utilized.

The results revealed that the short time of conditioning with the bacteria solution prior to conditioning with the flotation reagents was beneficial: depression was much more pronounced and flotation dropped to 16-18% (which is the level of mechanical carry over in this cell). A short conditioning with H_2SO_4 followed by conditioning with the flotation reagents provided even better flotation results. Conditioning with H_2SO_4 solution containing 2-5 g/l of Fe^{3+} ions did not cause any visible depression, but a further increase in Fe^{3+} concentration up to 10 g/l depressed pyrite floatability quite markedly. Thus, these results show that the treatment with bacteria solution depresses floatability probably due to the high concentration of Fe^{3+} ions and not necessarily to the effect of bacteria itself.

DISCUSSION

As our flotation tests showed (Fig. 8), the pyrite separated from Prince Mine coal did not float over the entire pH range when only kerosene and MIBC were employed. It must however be borne in mind that the -150 +50 μm size fraction was used in these experiments. As claimed by Rastogi and Aplan [2] both the coal flotation rate and pyrite flotation rate depend on pulp aeration. Consequently our Hallimond tube results do not necessarily reflect the behavior of much finer pyrite particles under real conditions of coal flotation.

The main conclusion, that the pyrite rejection is closely correlated with the ash rejection (Figs. 6 and 9), seems however, to confirm that the pyrite studied was hydrophilic and not floatable. If that is so, the main mechanism by which pyrite could report to the froth in our tests was entrainment and this can be reduced by controlling frothing and froth stability. The final conclusion is then perfectly in line with previous observations: in the flotation of finely ground coal, consumption of frother must be kept as low as possible and consequently rather large quantities of oily collector must be utilized.

The surface chemistry of pyrite was also studied with ESCA spectroscopy [18,19]. As Fe2p spectra revealed [19], the surface of the wet ground pyrite, or pyrite conditioned at pH 12, was covered with a hydroxide layer. The freshly dry ground pyrite, or pyrite

conditioned at pH 3, was shown to be quite different. S2p peaks confirm that pyritic sulphur is present on the surface of freshly dry ground pyrite, whereas sulphur oxidation products, such as sulphate, appear on wet ground samples, or samples conditioned in alkaline solutions.

Thanks to Dr. Frost (UBC Department of Chemistry), who pioneered the use of ESCA spectroscopy in studies on pyrite surface chemistry, the surface evolution of pyrite during the conditioning stage was also followed by ESCA spectroscopy (Fig. 10). As these preliminary tests show, both sulphate and pyritic sulphur peaks appear on S2p spectra of the pyrite used in our tests. While the sulphate peak decreases markedly for the pyrite treated in the sulphuric acid solution, the pyrite treated in the bacteria solution shows a decrease in the S^{2-} peak and only a slight depression of the SO^{2-}_4 peak. Thus, this observation confirms that the treatment with acid cleans the surface of pyrite of oxidation products [19] and that this cleaning is somewhat inhibited in the bacteria solution. It also explains the poor floatability of the pyrite used in the tests, and its much better flotation properties after conditioning with sulphuric acid (Tables 4 and 5). As shown, the treatment with sulphuric acid solution can inhibit pyrite floatability when the solution also contains a high concentration of Fe^{3+} ions which seems to explain the depressing effect of the bacteria solutions on pyrite floatability as the concentration of iron ions in these solutions is clearly very high.

CONCLUSIONS

1. A good correlation between pyrite and ash rejections indicates that the Prince Mine coal pyrite floats poorly.

2. Low pyritic sulphur content in the cleaned coal (below 0.5%) can be obtained by fine grinding of the coal and careful control of the entrainment in the flotation process.

3. Conditioning with the bacteria solution affects coal flotation selectivity presumably through enhancement of the entrainment contribution to overall flotation recovery.

4. Flotation experiments on pyrite separated from the Prince Mine coal confirmed that it does not float when only kerosene and MIBC are used. While pretreatment of such pyrite with sulphuric acid enhances its floatability with xanthate and kerosene, pretreatment with sulphuric acid solution containing a high concentration of ferric ions (10 g/l) inhibits its flotation.

ACKNOWLEDGEMENT

Dr. D. Frost and his team (UBC Chemistry Department) are thanked for the XPS Spectra of coal-pyrite.

REFERENCES

1. L. J. Warren, "Ultrafine particles in flotation" in "Principles of Mineral Flotation" (M.H. Jones and J. T. Woodcock, eds). Australaisan Institute of Mining and Metallurgy, (1984), pp. 185-214.

2. R.C. Rastogi and F.F. Aplan, "Coal flotation as a rate process", Minerals and Metallurgical Processing, p. 137, (August, 1985).

3. S.R. Taylor, K.J. Miller and A.W. Deurbrouck, "Surface chemical problems in coal flotation" in "Chemistry and Physics of Coal Utilization - 1980" (B.R. Cooper and L. Petrakis eds.) Am. Inst. Physics, (1981), pp. 344-356.

4. J.D. Miller and C.C. Liu, "Characterization of pyrite in products from the reverse flotation of coal", Coal Preparation, (1986), 2 243.

5. A.C. Kempton, C.E. Capes and R.G.L. McCready, "Removal of pyrite from coal by conditioning with Thiobacillus Ferrooxidans followed by oil agglomeration", Hydrometallurgy, 5, 117, (1980).

6. Y.A. Attia and M.A. Elzeky, "Biosurface modification in the separation of pyrite from coal by froth flotation", Proceedings of the First International Conference on Processing and Utilization of High Sulfur Coals, Elsevier, (1985), pp. 673-682,

7. M.Z. Dogan et al. "Bacterial leaching versus bacterial conditioning and flotation in desulphurization of coal", XVth International Mineral Processing Congress, 2, 304 (1985).

8. L.E. Murr and V.K. Berry, "Direct observations of selective attachment of bacteria to low-grade sulfide ore and other mineral surfaces", Hydrometallurgy, (1976), 2, 11.

9. R.G.L. McCready and B.P. LeGallais, "Selective adsorption of ^{32}P-labelled Thiobacillus Ferrooxidans in finely ground coal suspensions, Hydrometallurgy, 12, 281, (1984).

10. G.E. Jones, and R.L. Starkey, "Surface active substances produced by Thiobacillus Thiooxidans", Journal of Bacteriology, 82, 788 (1961).

11. W.I. Schaeffer and W.W. Umbriet, "Phosphotidylinositol as a wetting agent in sulfur oxidation by Thiobacillus Thiooxidans", Journal of Bacteriology, 85, 492 (1963).

12. C. Schnaitman and D.G. Lundgren, "Organic compounds in the spent medium of Ferrobacillus Ferroxidans", Canadian Journal of Mircrobiology, 11, 23 (1965).

13. J.M. Shively and A.A. Benson, "Phospholipids of Thiobacillus Thioxidans", Journal of Bacteriology", 94, No. 5, p. 1679 (1957).

14. J.L. Beebe and W.W. Umbreit, "Extracellular Lipids of Thiobacillus Thiooxidans", Journal of Bacteriology, 108, No. 7, 612 (1971).

15. J. Laskowski, M. Bustin, K. Moon and L.L. Sirois, "Desulphurizing flotation of Eastern Canadian high sulphur coal", in "Processing and Utilization of High Sulphur Coals", (Y.A. Attia. ed.) Elsevier, (1985), pp. 247-266.

16. T. Roberts, B.A. Firth and S.K. Nicol, "A modified laboratory cell for the flotation of coal", Int. J. Min. Processing, 9, 191 (1982).

17. J.S. Laskowski, "Beneficiation of ultrafine high sulphur coal", DSS Contract OST84-00161, 1984.

18. D.C. Frost, W.R. Leeder, R.L. Tapping and B. Wallbank, "An XPS study of the oxidation of pyrite and pyrites in coal", Fuel, 56, 277 (1977).

19. D. Brion, J. Hayer and J.J. Predali, "Characterization by ESCA of surface compounds of fine pyrite during the flotation process", "Fine Particles Processing", (P. Somasundaran ed.), AIME, (1980), Vol. 1, pp. 544-557 (1980).

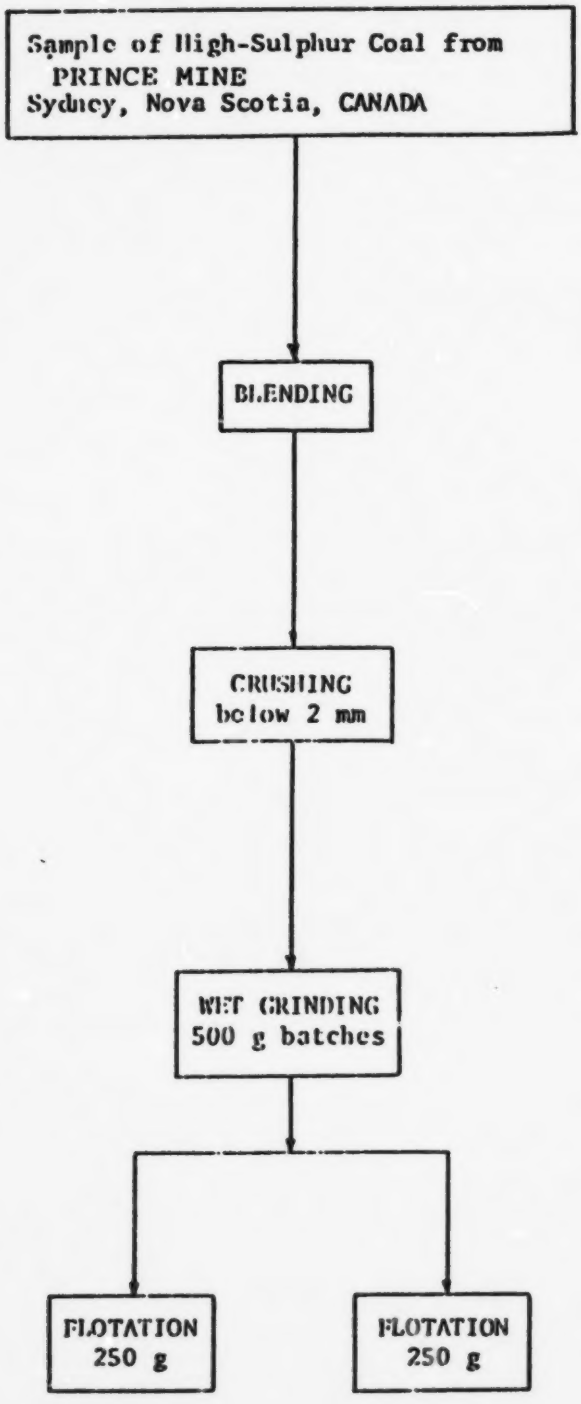


Figure 1. - Coal Preparation Procedure for Flotation Experiments

(from reference 17)

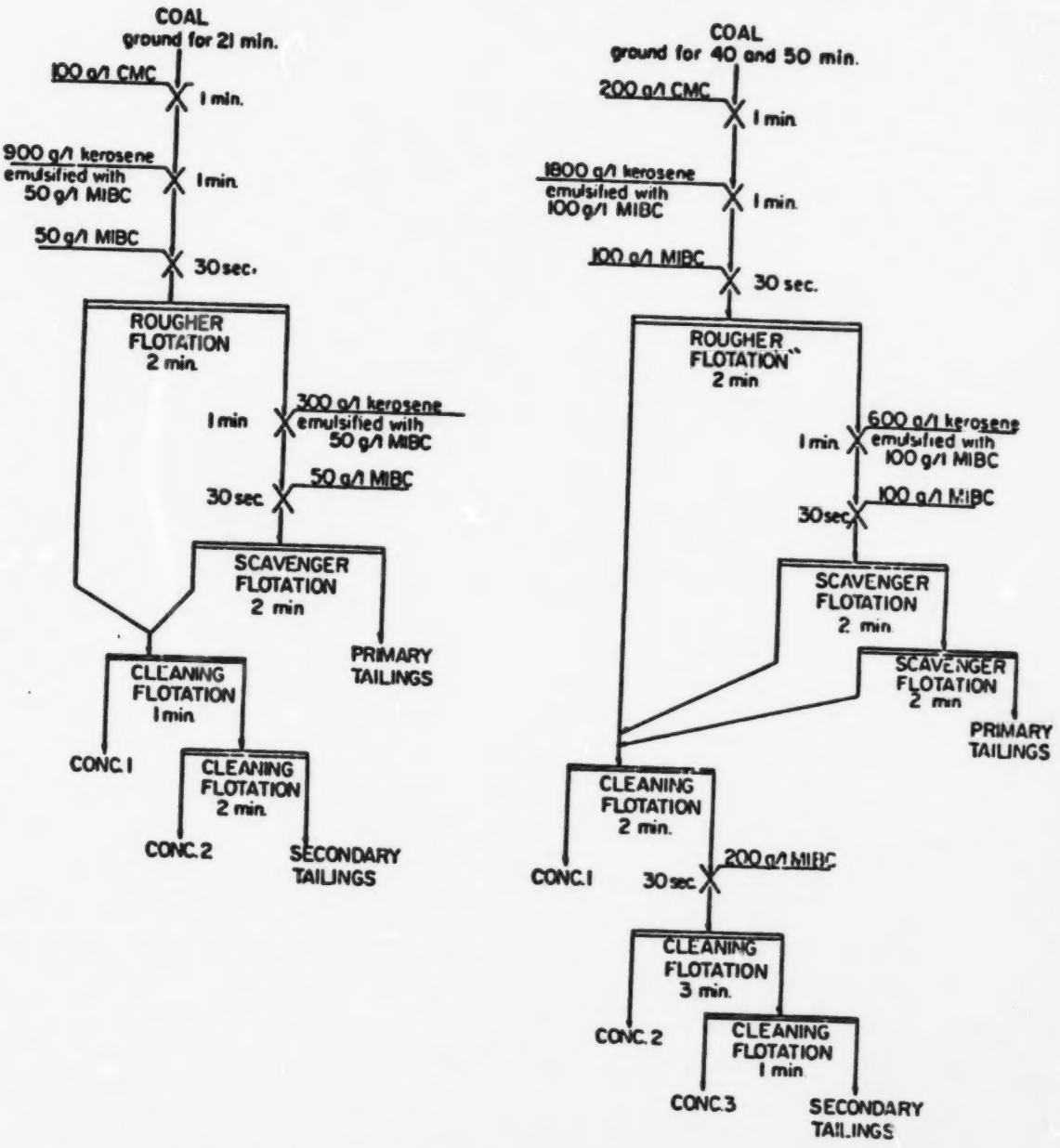


Fig. 2 Schematic illustration of the batch flotation procedures with the use of CMC, kerosene and MIBC

(from reference 17)

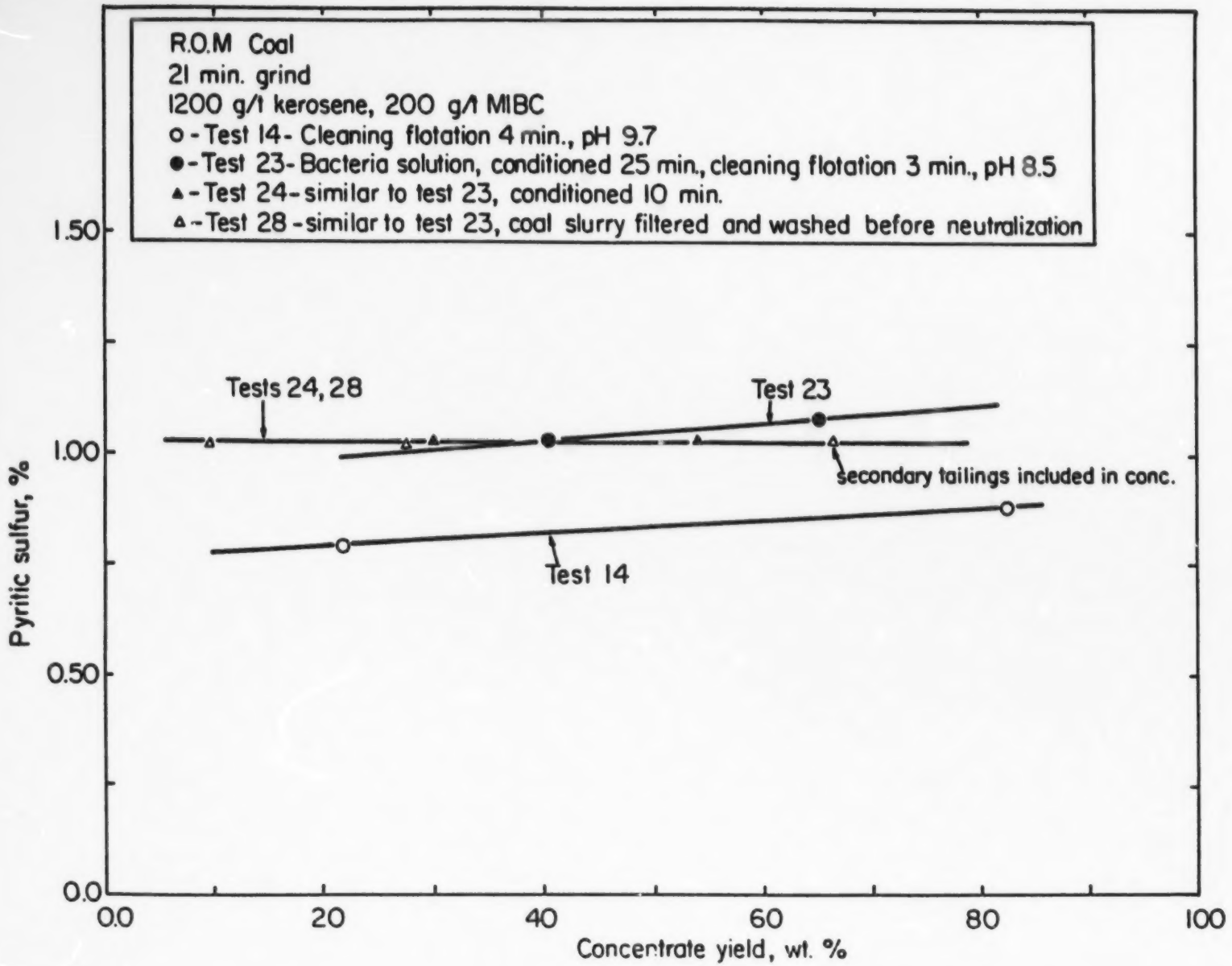

R.O.M Coal
21 min. grind
1200 g/t kerosene, 200 g/t MIBC
o - Test 14 - Cleaning flotation 4 min., pH 9.7
● - Test 23 - Bacteria solution, conditioned 25 min., cleaning flotation 3 min., pH 8.5
▲ - Test 24 - similar to test 23, conditioned 10 min.
△ - Test 28 - similar to test 23, coal slurry filtered and washed before neutralization
Tests 24, 28
Test 23
secondary tailings included in conc.
Test 14
Pyritic sulfur, %
1.50
1.00
0.50
0.0
0.0
20
40
60
80
100
Concentrate yield, wt. %

Figure 3. The effect of conditioning with bacteria solution on the pyrite in the clean coal concentrate.

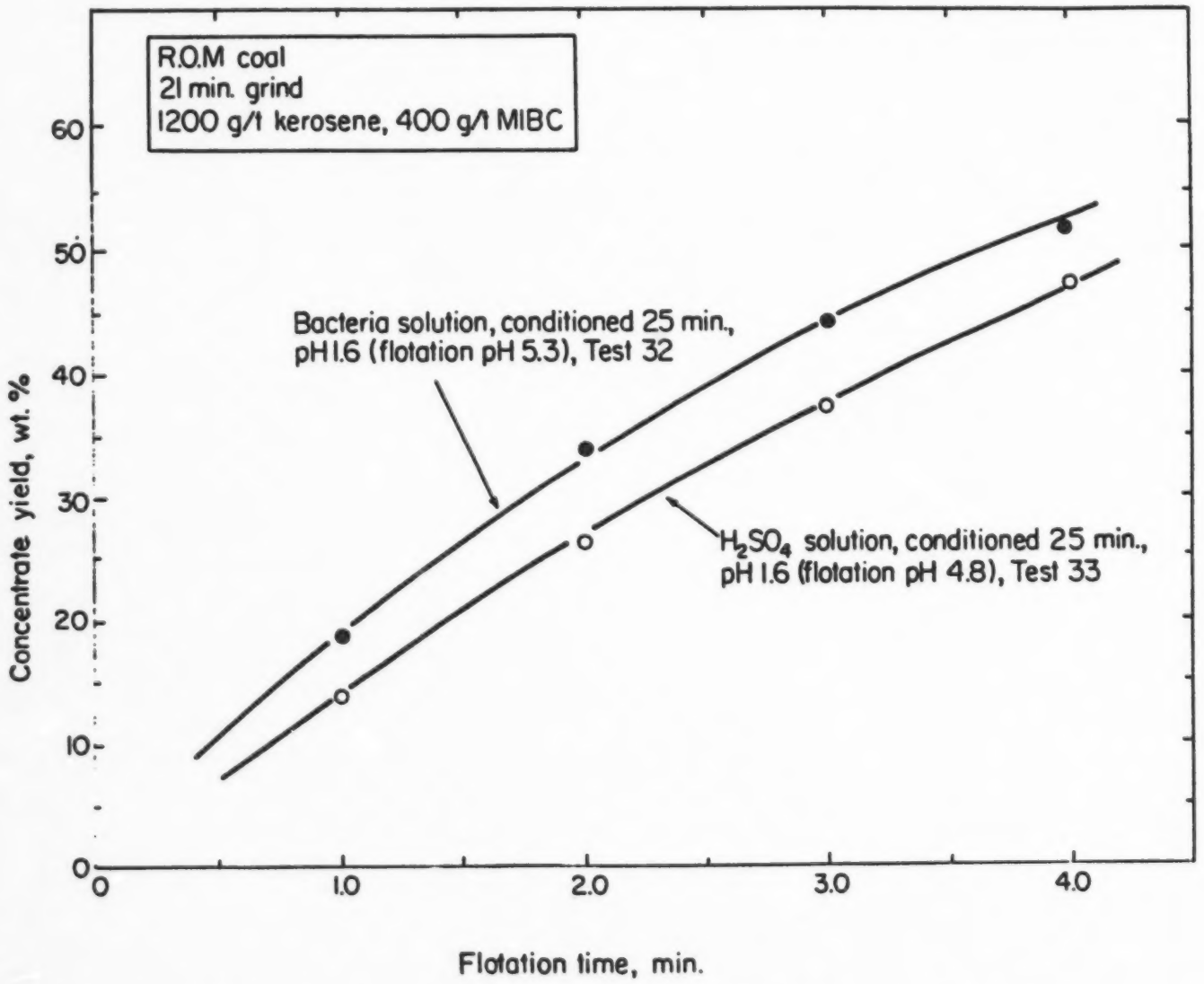


Figure 4. The effect of conditioning with bacteria solution and H_2SO_4 on the kinetics of flotation.

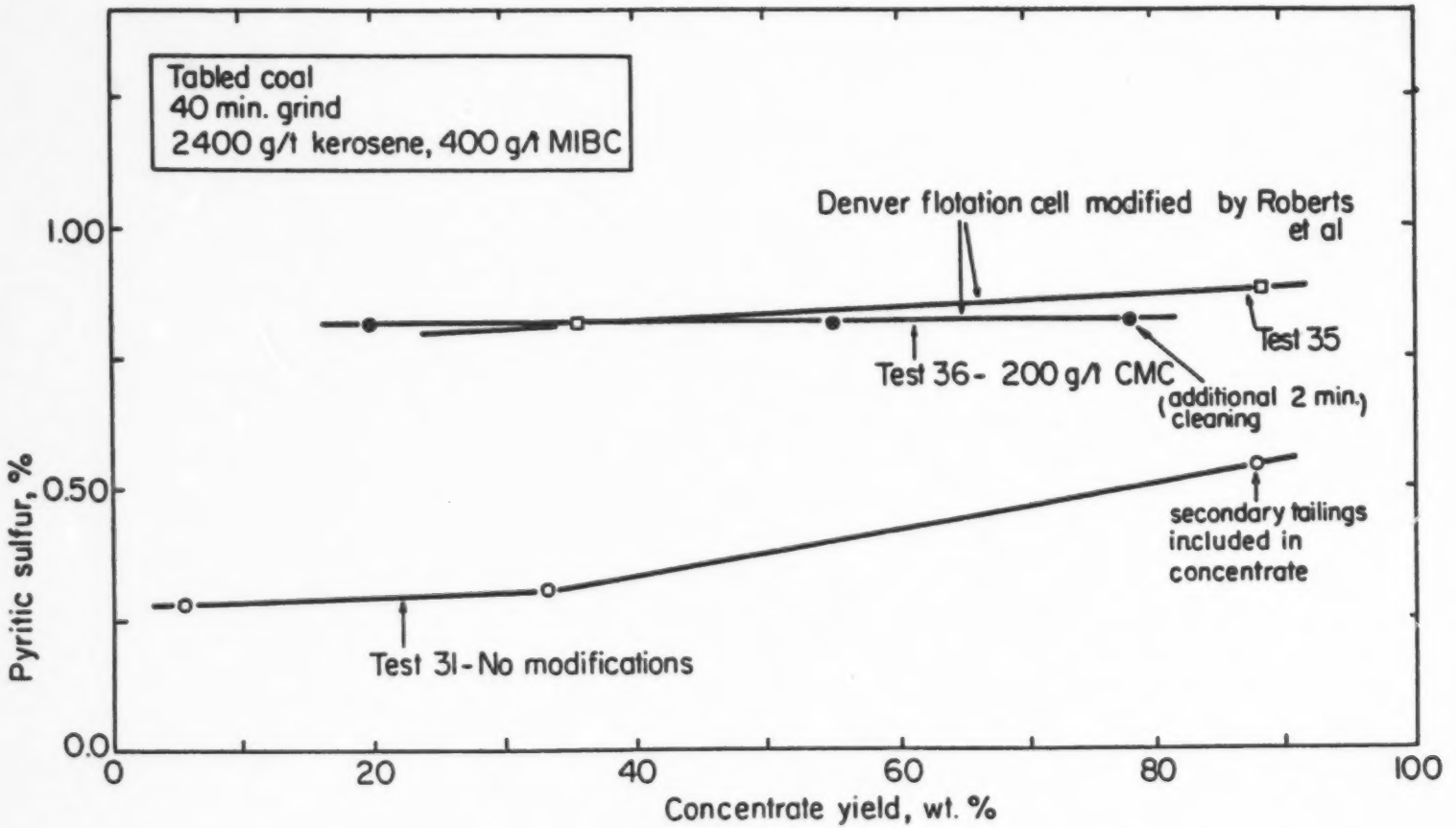


Figure 5. The effect of the modifications made by Roberts et al[12] on the pyrite level in the clean coal concentrate.

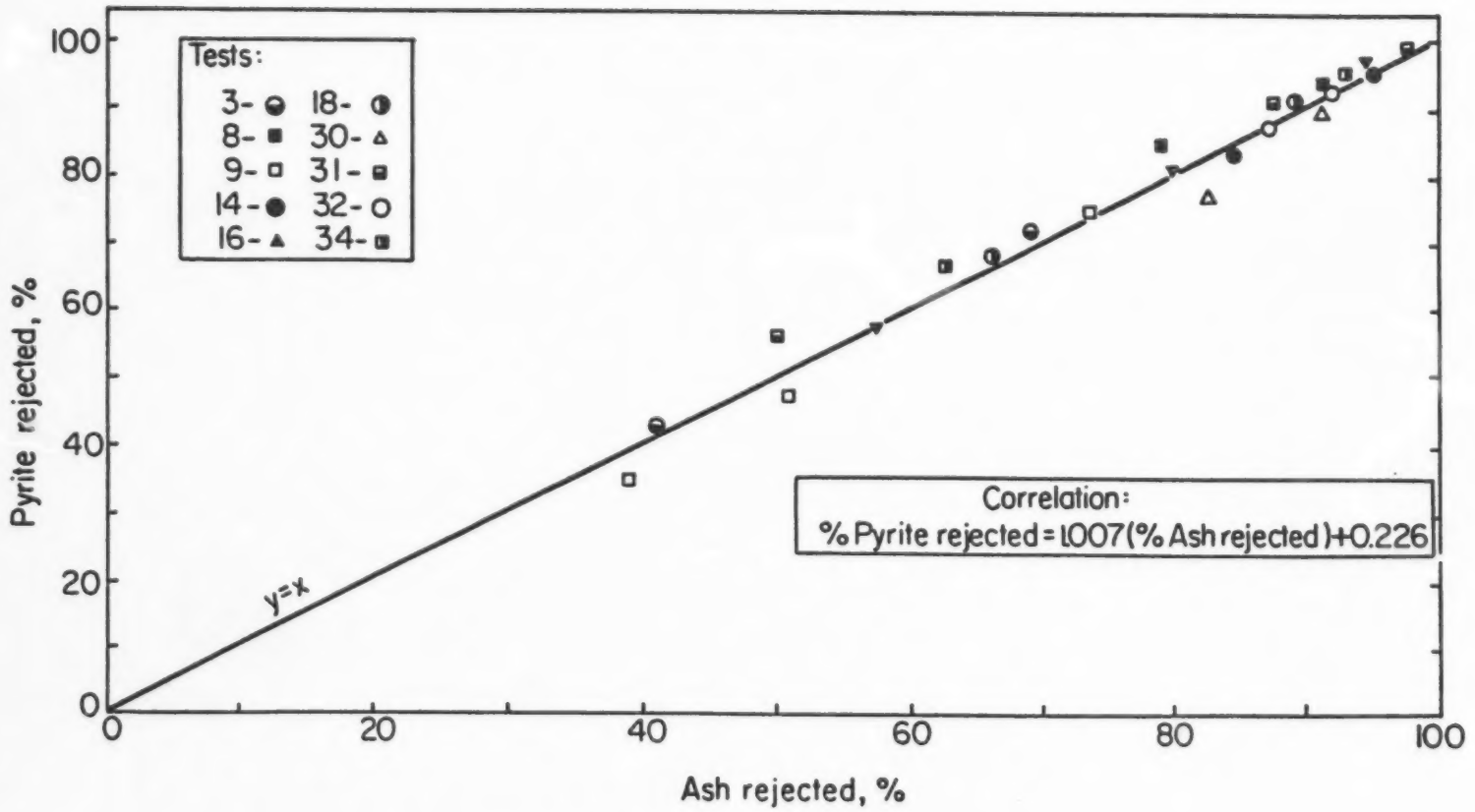


Figure 6. Correlation between ash and pyrite rejection for the Prince Mine coal.

Test conditions and data used in Figure 6

Test·

3/ As outlined in Figure 2a with no cleaning flotation, pH-9.0

	wt%	Pyritic S%	Ash%
conc 1	53.6	1.38	9.9
conc 2	39.1	2.64	14.4
tailings-Primary	7.4	9.99	81.6

8/ As outlined in Figure 2a pH-9.0

	wt%	Pyritic S%	Ash%
conc 1	21.8	0.80	6.94
conc 2	27.2	0.92	7.41
tailings-Primary	13.6	8.95	56.0
Secondary	37.4	2.53	14.51

9/ As outlined in Figure 2a pH-9.3

	wt%	Pyritic S%	Ash%
conc 1	56.4	1.15	10.1
conc 2	29.9	2.76	17.4
conc 3	3.5	10.56	73.0
tailings-Primary	6.9	9.4	83.0
Secondary	3.3	8.7	82.4

14/ As outlined in figure 2a , no CMC, pH-8.7 and an additional 1 minute of cleaning for concentrate 2

	wt%	Pyrytic S%	Ash%
conc 1	23.5	0.80	6.93
conc 2	58.7	0.92	6.22
tailings-Primary	9.8	10.33	69.83
Secondary	8.0	6.66	47.33

16/ As outlined in Figure 2a , 2xCMC, pH-9.1 concentrate 1 - 1 minute, concentrate 2-3 minutes and 2 minutes for concentrate 3.

	wt%	Pyritic S%	Ash%
conc 1	9.3	1.26	9.1
conc 2	28.2	1.38	9.5
conc 3	21.7	1.38	9.4
tailings-Primary	26.3	4.92	34.2
Secondary	14.5	3.21	22.8

18/ As outlined in Figure 2a , no CMC pH-8.8

	Wt%	Pyritic S%	Ash%
conc 1	15.4	0.69	6.38
conc 2	31.4	0.80	6.06
tailings-Primary	14.9	6.66	64.6
-Secondary	38.3	2.30	15.22

30/ As outlined in Figure 2a., no CMC, pH-7.8 modifications made by Roberts et al removed and concentrate 3 an additional 2 minutes of cleaning.

	Wt%	Pyritic S%	Ash%
conc 1	11.9	0.50	3.64
conc 2	26.6	0.60	3.57
conc 3	33.8	0.80	4.15
tailings-Primary	20.0	7.35	58.1
Secondary	7.7	4.48	28.4

31/ As outlined in Figure 2a , tabled coal ground 40 minutes pH-6.7, 2x reagents, no CMC.

	Wt%	Pyritic S%	Ash%
conc 1	5.52	0.29	1.83
conc 2	27.4	0.34	1.61
tailings-Primary	13.1	5.85	22.5
Secondary	54.0	0.8	3.36

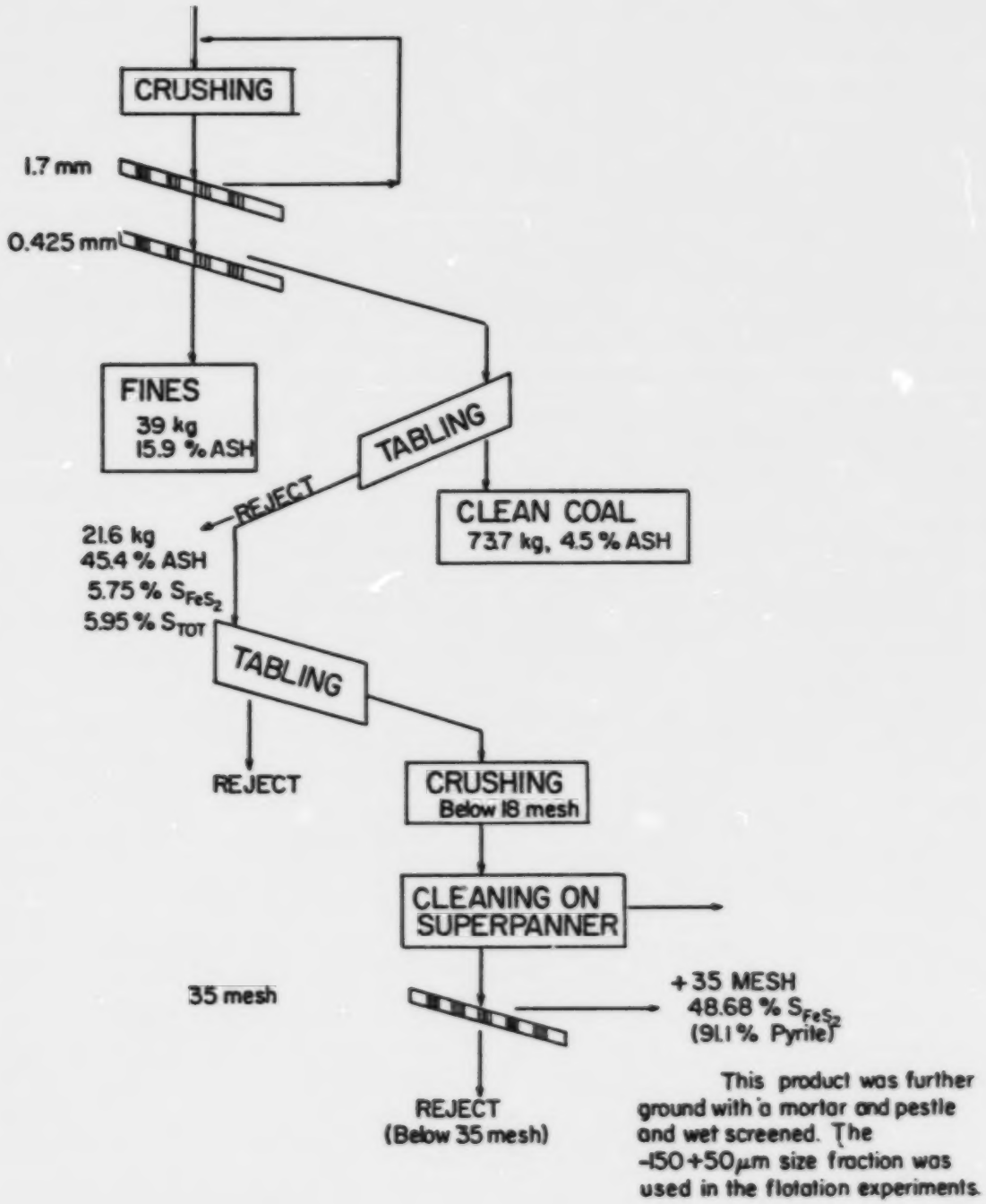
32/ As outlined in Figure 2a , no CMC, conditioned with bacteria 25 minutes at pH 1.6, filtered and washed and floated at pH-5.3, cleaning flotation for concentrates 1 minute each.

	Wt%	Pyritic S%	Ash%
conc 1	18.4	1.03	5.79
conc 2	15.7	0.92	5.32
conc 3	9.8	1.03	5.15
conc 4	8.1	1.03	4.710
tailings-Primary	17.3	8.5	52.50
Secondary	30.7	2.87	14.10

34/ As outlined in Figure 2a , with no cleaning stages, no cmc 2x reagents, modifications removed pH-4.8 natural (coal & tap water), tabled coal ground 40 minutes.

	Wt%	Pyritic S%	Ash%
conc 1	12.4	0.57	3.5
conc 2	69.2	0.57	3.2
Tailings	18.4	4.82	23.8

Fig. 7 Separation of pyrite from coal



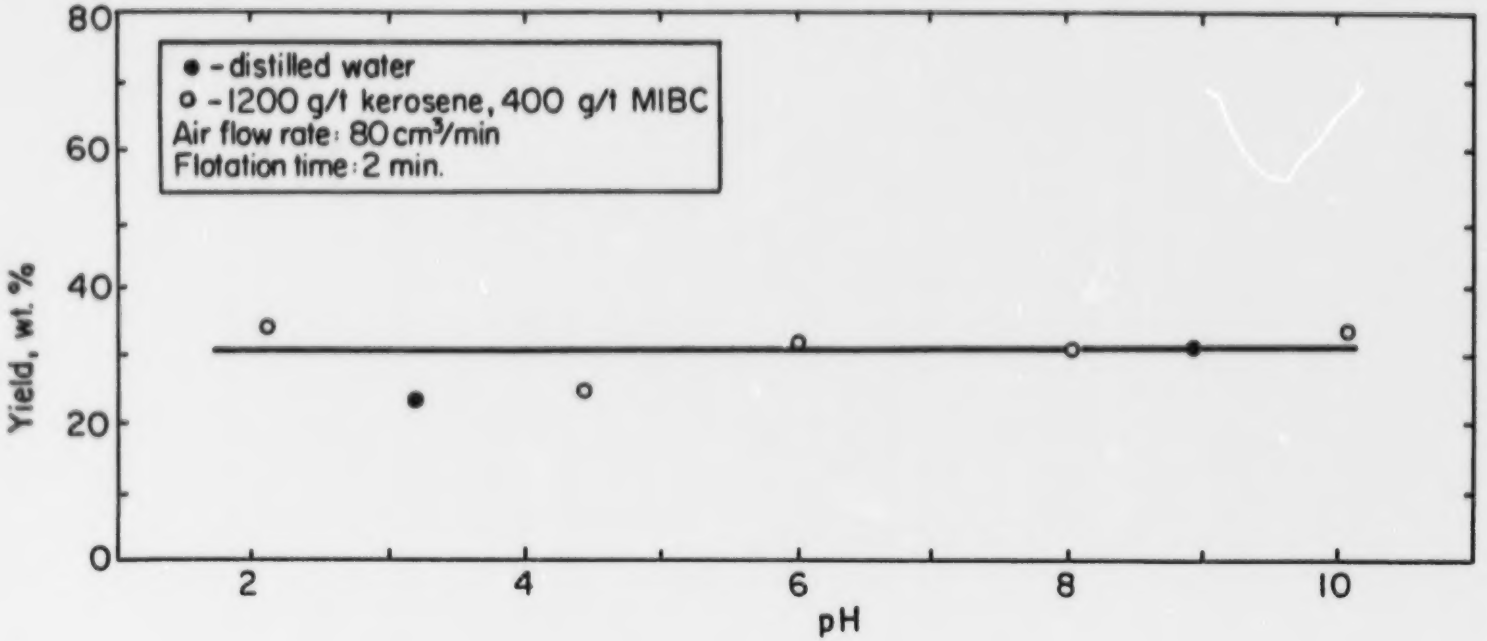


Figure 8: Hallimond tube tests with pure pyrite (50-150μm).

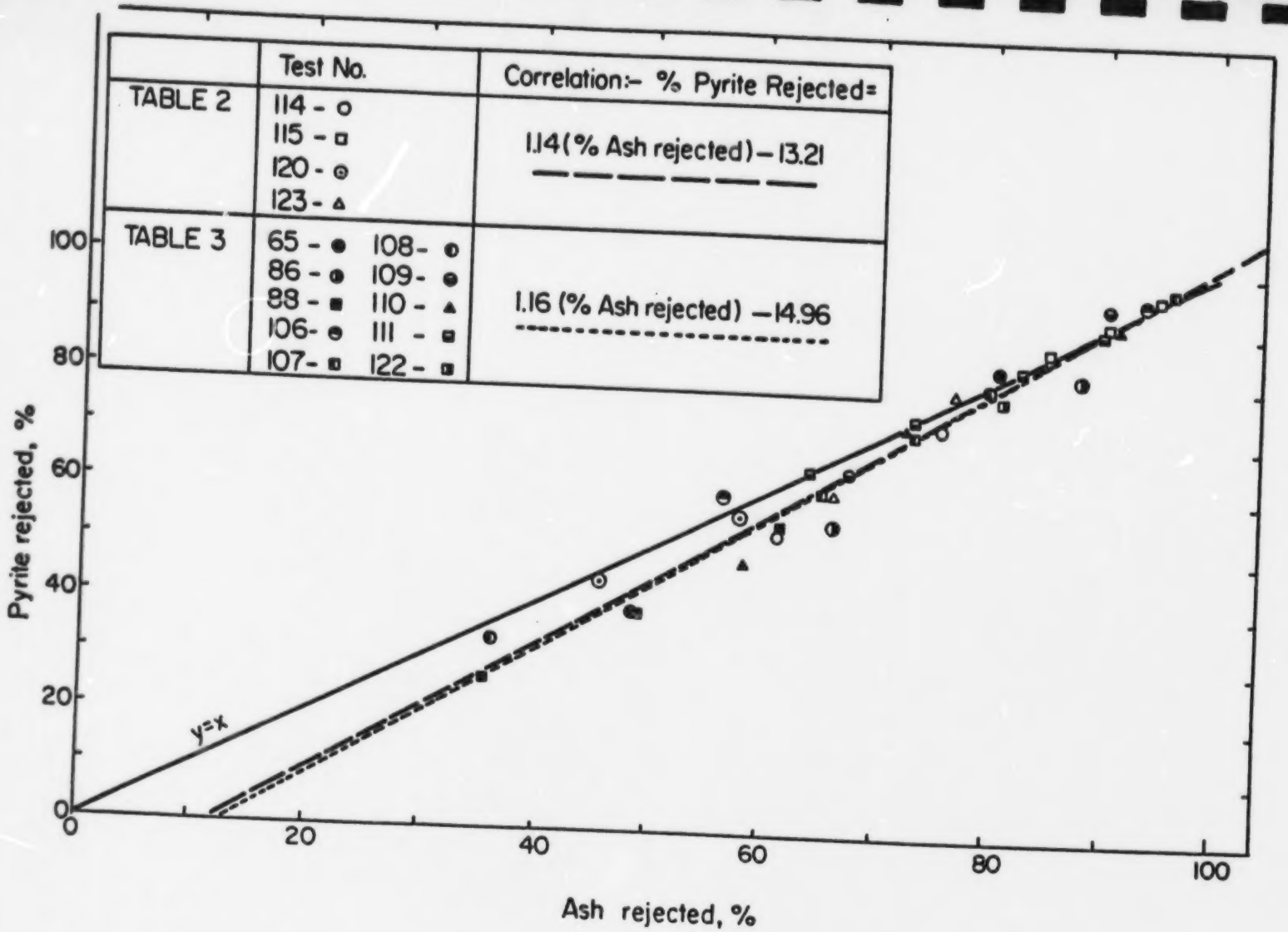


Figure 9. Correlation between ash and pyrite rejection for the Prince Mine coal (Data from reference 11, Tables 2&3).

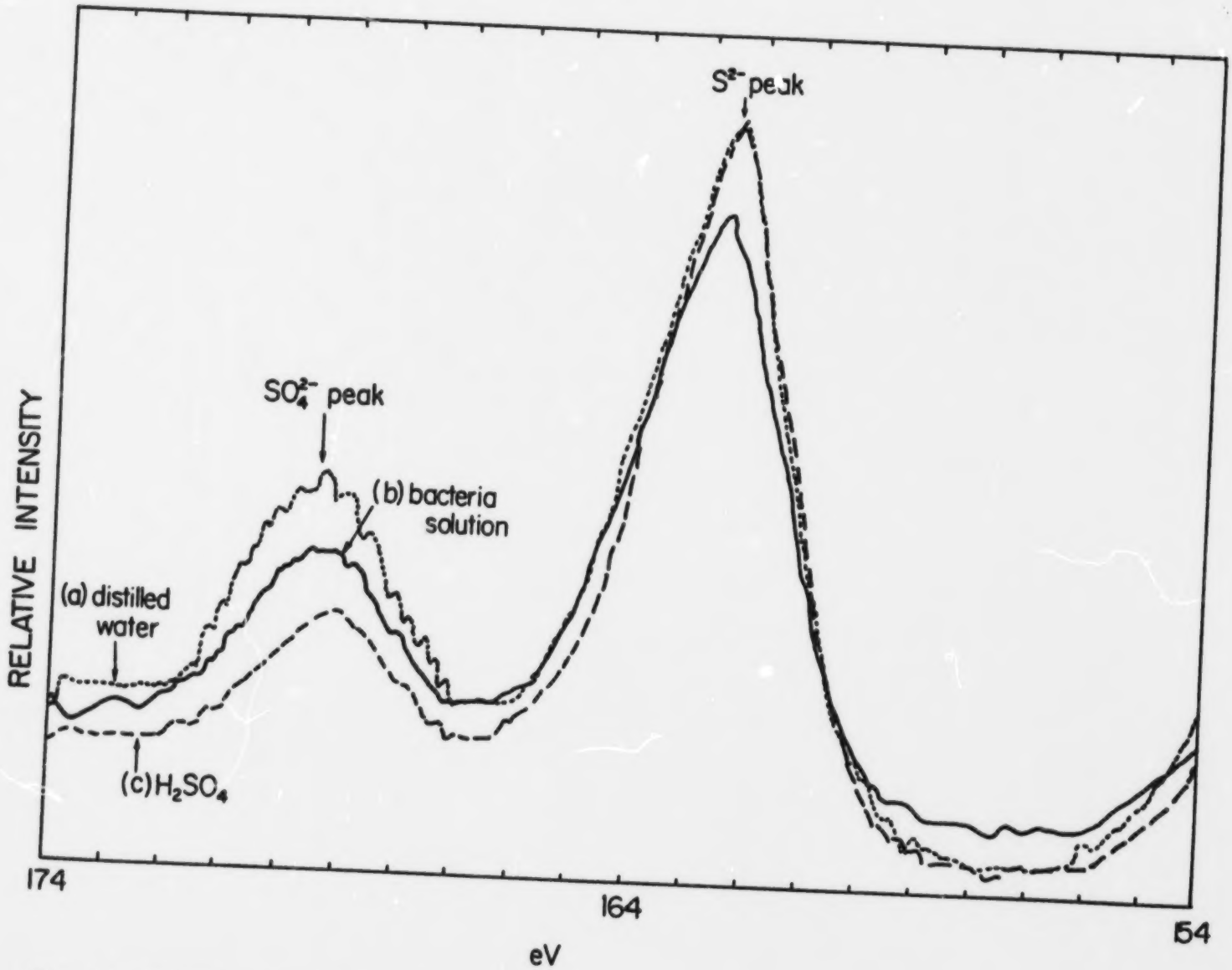


Fig. 10 S2p XPS Spectra for coal pyrite conditioned in distilled water (a), in the bacteria solution (b) and in sulphuric acid (c).

Table 1

	A ROM Prince Mine Coal	B Prince Mine Coal cleaned by tabling (-1.7mm)	C ROM Prince Mine Coal Previously studied [17]
Moisture %	1.85	2.33	1.64
Volatiles (dry)%	24.2	29.1	28.1
Ash (dry)%	14.4	4.5	13.2
Fixed Carbon (dry)%	61.4	66.7	58.7
Volatiles (dmmf)%	28.27	30.3	32.37
Fixed Carbon (dmmf)%	71.73	69.7	67.63
Pyritic Sulfur%	2.55	1.35	2.76
Total Sulfur%	3.60	2.60	3.7
F.S.I.	6.0	6.50	

Tables 2 & 3

(from Roberts et al [16] paper)

TABLE 2

Modified cell

Test No.	Mass of solids in feed (gms)	Flotation Product				Tailings		Composite	
		Mass of wet froth (gms)	Mass of dry solids (gms)	Yield (wt %)	Ash* (% db)	Mass of dry solids (gms)	Ash (% db)	Mass[1] (wt %)	Ash[2] (% db)
	(1)	(2)	(3)	100 x (3)/(1)	(4)	(5)	(6)	100[(3) + (5)]/(1)	[(3) x (4) + (5) x (6)]/[(3) + (5)]
F1	210	399.1	133.9	63.8	14.1	70.4	61.5	97.3	30.4
F2	210	429.9	134.4	64.0	14.1	67.5	63.3	96.1	30.5
F3	210	455.2	136.4	64.9	13.7	65.3	62.9	96.0	29.6
F4	210	469.2	137.9	65.7	13.7	65.4	62.1	96.8	29.3
F5	210	444.3	136.6	65.0	13.5	65.1	61.7	96.0	29.1
F6	210	485.5	137.1	65.3	13.6	66.3	62.1	96.9	29.4
$\bar{x}$		447.2	136.1	64.8	13.8	66.7	62.3	96.5	29.7
S		30.5	1.6	0.7	0.3	2.0	0.7	0.6	0.6

TABLE 3

Unmodified cell

Test No.	Mass of solids in feed (gms)	Flotation product				Tailings		Composite	
		Mass of wet froth (gms)	Mass of dry solids (gms)	Yield (wt %)	Ash* (% db)	Mass of dry solids (gms)	Ash (% db)	Mass[1] (wt %)	Ash[2] (% db)
	(1)	(2)	(3)	100 x (3)/(1)	(4)	(5)	(6)	100[(3) + (5)]/(1)	[(3) x (4) + (5) x (6)]/[(3) + (5)]
F7	251	483.1	156.0	62.2	12.3	86.5	62.3	96.7	30.2
F8	251	501.3	159.8	63.7	13.1	83.7	60.6	97.0	29.4
F9	251	571.4	164.5	65.5	13.5	78.1	61.7	96.7	29.0
F10	251	542.9	159.5	63.5	13.0	83.6	60.5	96.8	29.3
F11	251	577.9	163.1	65.0	13.3	80.5	62.0	97.0	29.4
F12	251	659.4	163.6	65.2	13.8	79.8	61.8	97.0	29.5
$\bar{x}$		556.0	161.1	64.2	13.2	82.1	61.5	96.9	29.5
S		63.1	3.2	1.3	0.5	3.1	0.7	0.2	0.4

[1] Calculated as a check on the mass-balance.
[2] Calculated as a check on the ash-balance.
*(db) dry basis.

Table 4

Flotation of Pyrite with KAmX (0.2 kg/t) and Kerosene (6.0 kg/t), Airflow rate 30 cc/min.

No	Conditioning (25 min)	Flotation reagents	Flotation pH	Pyrite recovery (after 2 min)
1	Distilled water	No	5.1	12.6
2	Distilled water	KAmX	5.3	25.5
3	Distilled water	KAmX+Kerosene	5.1	78.5
4	Bacteria sol.	KAmX+Kerosene	4.9	42.6
5	H_2SO_4 sol.	KAmX+Kerosene	4.7	85.4

Table 5

Flotation of Pyrite with KAmX (0.2 kg/t) and Kerosene (6.0 kg/t), Airflow rate 30 cc/min.

No	Conditioning (25 min)	Flotation reagents	Flotation pH	Pyrite Recovery (after 2 min)
1	Distilled water	KAmX+Kerosene	5.0	71.7
2	Distilled water*	KAmX+Kerosene	5.9	77.4
3	Distilled water*	KAmX+Kerosene	5.0	80.8
4	Bacteria sol.	KAmX+Kerosene	5.4	30.7
5	Bacteria sol.*	KAmX+Kerosene	5.0	37.1
6	Bacteria sol.	KAmX+Kerosene	5.0	27.1
7	Bacteria sol. 15 min conditioning	KAmX+Kerosene	5.0	18.7
8	Bacteria sol.* 5 min conditioning	KAmX+Kerosene	5.0	18.4
9	Bacteria sol. 2.5 min cond.	KAmX+Kerosene	5.0	14.0
10	Bacteria sol.* 1 min conditioning	KAmX+Kerosene	5.0	16.6
11	H_2SO_4 + $Fe_2(SO_4)_3$ 6 g/l Fe	KAmX+Kerosene	5.3	78.2
12	H_2SO_4 10g/l Fe^{3+}(*)	KAmX+Kerosene	5.0	45.6
13	H_2SO_4 10g/l Fe^{3+}(*) 5 min conditioning	KAmX+Kerosene	5.0	28.2
14	H_2SO_4 2.5 min	KAmX+Kerosene	5.0	94.2
15	H_2SO_4 for 2.5 min 10 g/l Fe^{3+}	KAmX+Kerosene	5.0	28.4
	5 g/l Fe^{3+}	KAmX+Kerosene	5.0	83.6
	2 g/l Fe^{3+}	KAmX+Kerosene	5.0	78.5

*Pyrite was separated from solution by centrifuging